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PROCEEDINGS OF NRC ANNUAL PROBABILISTIC FLOOD HAZARD ASSESSMENT RESEARCH WORKSHOPS I-IV

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***Part 3:** Third Annual NRC Probabilistic Flood Hazard Assessment Research Workshop*

Research Information Letter
Research Office of Nuclear Regulatory Research

Disclaimer

ABSTRACT

The U.S. Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research (RES) is conducting a multiyear, multi-project Probabilistic Flood Hazard Assessment (PFHA) Research Program to enhance the NRC's risk-informed and performance-based regulatory approach with regard to external flood hazard assessment and safety consequences of external flooding events at nuclear power plants (NPPs). It initiated this research in response to staff recognition of a lack of guidance for conducting PFHAs at nuclear facilities that required staff and licensees to use highly conservative deterministic methods in regulatory applications. Risk assessment of flooding hazards and consequences of flooding events is a recognized gap in NRC's risk-informed, performance-based regulatory framework. The objective, research themes, and specific research topics are described in the RES Probabilistic Flood Hazard Assessment Research Plan. While the technical basis research, pilot studies and guidance development are ongoing, RES has been presenting Annual PFHA Research Workshops to communicate results, assess progress, collect feedback and chart future activities. These workshops have brought together NRC staff and management from RES and User Offices, technical support contractors, as well as interagency and international collaborators and industry and public representatives.

These conference proceedings transmit the agenda, abstracts, presentation slides, summarized questions and answers, and panel discussion for the first four Annual U.S. Nuclear Regulatory Commission (NRC) Probabilistic Flood Hazard Assessment Research Workshops held at NRC Headquarters in Rockville, MD. The workshops took place on October 14–15, 2015; January 23–25, 2017; December 4–5, 2017; and April 30–May 2, 2019. The first workshop was an internal meeting attended by NRC staff, contractors, and partner Federal agencies. The following workshops were public meetings and attended by members of the public; NRC technical staff, management, and contractors; and staff from other Federal agencies. All of the workshops began with an introductory session that included perspectives and research program highlights from the NRC Office of Nuclear Regulatory Research and also may have included perspectives from the NRC Office of New Reactors and Office of Nuclear Reactor Regulation, the Electric Power Research Institute (EPRI), and industry representatives. NRC and EPRI contractors and staff as well as invited Federal and public speakers gave technical presentations and participated in various styles of panel discussion. Later workshops included poster sessions and participation from academic and interested students. The workshops included five focus areas:

(1) leveraging available flood information
(2) evaluating the application of improved mechanistic and climate probabilistic modeling for storm surge, climate and precipitation
(3) probabilistic flood hazard assessment frameworks
(4) potential impacts of dynamic and nonstationary processes
(5) assessing the reliability of flood protection and plant response to flooding events

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ABBREVIATION AND ACRONYMS

σ	sigma, standard deviation
°C	degrees Celsius
°F	degrees Fahrenheit
^{13}C-NMR	carbon-13 nuclear magnetic resonance
^{14}C	carbon-14
17B	Guidelines for Determining Flood Flow Frequency—Bulletin 17B, 1982
17C	Guidelines for Determining Flood Flow Frequency—Bulletin 17C, 2018
1-D	one dimensional
20C	20th Century Reanalysis
2BCMB	Level 2—DPR and GMI Combine
2-D	two dimensional
3-D	three dimensional
AAB	Accident Analysis Branch in NRC/RES/DSA
AB	auxiliary building
AC, ac	alternating current
ACCP	Alabama Coastal Comprehensive Plan
ACE	accumulated cyclone energy, an approximation of the wind energy used by a tropical system over its lifetime
ACM	alternative conceptual model
ACME	Accelerated Climate Modeling for Energy (DOE)
ACWI	Advisory Committee on Water Information
AD	anno Domini
ADAMS	Agencywide Documents Access and Management System
ADCIRC	ADvanced CIRCulation model
AEP	annual exceedance probability
AEP4	Asymmetric Exponential Power distribution
AFW	auxiliary feedwater
AGCMLE	Assistant General Counsel for Materials Litigation and Enforcement in NRC/OGC/GCHA
AGCNRP	Assistant General Counsel for New Reactor Programs in NRC/OGC/GCHA
AGFZ	Azores–Gibraltar Transform Fault
AGL	above ground level
AIC	Akaike Information Criterion

AIMS	assumptions, inputs, and methods
AIRS	Advanced InfraRed Sounder
AIT	air intake tunnel
AK	Alaska
AM	annual maxima
AMJ	April, May, June
AMM	Atlantic Meridional Mode
AMO	Atlantic Multi-Decadal Oscillation
AMS	annual maxima series
AMSR-2	Advance Microwave Scanning Radiometer
AMSU	Advanced Microwave Sounding Unit
ANN	annual
ANO	Arkansas Nuclear One
ANOVA	analysis of variance decomposition
ANS	American Nuclear Society
ANSI	American National Standards Institute
ANVS	Netherlands Authority for Nuclear Safety and Radiation Protection
AO	Assistant for Operations in NRC/OEDO
AOP	abnormal operating procedure
APF	annual probability of failure
APHB	Probabilistic Risk Assessment Operations and Human Factors Branch
API	application programming interface
APLA/APLB	Probabilistic Risk Assessment Licensing Branch A/B in NRC/NRR/DRA
APOB	PRA Oversight Branch in NRC/NRR/DRA
AR	atmospheric river
AR	Arkansas
AR4, AR5	climate scenarios from the 4th/5th Intergovernmental Panel on Climate Change Reports / Working Groups
ARA	Applied Research Associates
ArcGIS	geographic information system owned by ESRI
ARF	areal reduction factor
ARI	average return interval
ARR	Australian Rainfall-Runoff Method
AS	adjoining stratiform
ASM	annual series maxima

ASME	American Society of Mechanical Engineers
ASN	French Nuclear Safety Authority (Autorité de Sûreté Nucléaire)
ASTM	American Society for Testing and Materials
ATMS	Advance Technology Microwave Sounder
ATWS	anticipated transient without scram
AVHRR	Advance Very High Resolution Radiometer
B&A	Bittner & Associates
BATEA	Bayesian Total Error Analysis
BB	backbuilding/quasistationary
BC	boundary condition
Bel V	subsidiary of Belgian Federal Agency for Nuclear Control (FANC)
BHM	Bayesian Hierarchical Model
BIA	Bureau of Indian Affairs
BMA	Bayesian Model Averaging
BQ	Bayesian Quadrature
BWR	boiling-water reactor
CA	California
CAC	common access card
CAPE	Climate Action Peer Exchange
CAPE	convective available potential energy
CAS	corrective action study
CAS2CD	CAScade 2-Dimensional model (Colorado State)
Cat.	category on the Saffir-Simpson Hurricane Wind Scale
CBR	center, body, and range
CC	Clausius-Clapeyron
CC	climate change
CCCR	Center for Climate Change Research
CCDP	conditional core damage probability
CCI	Coppersmith Consulting Inc.
CCSM4	Community Climate System Model version 4
CCW	closed cooling water
CDB	current design basis
CDF	core damage frequency
CDF	cumulative distribution function

CE	common era
CEATI	Centre for Energy Advancement through Technological Innovation
CEET	cracked embankment erosion test
CENRS	National Science and Technology Council Committee on Environment, Natural Resources, and Sustainability
CESM	Community Earth System Model
CFD	computational fluid dynamics
CFHA	comprehensive flood hazard assessment
CFR	*Code of Federal Regulations*
CFSR	Climate Forecast System Reanalysis
CHIPs	Coupled Hurricane Intensity Prediction System
CHiRPs	Climate Hazards Group infraRed Precipitation with Station Data
CHL	Coastal and Hydraulics Laboratory
CHRP	Coastal Hazard Rapid Prediction, part of StormSIM
CHS	Coastal Hazards System
CI	confidence interval
CICS-NC	Cooperative Institute for Climates and Satellites—North Carolina
CIPB	Construction Inspection Management Branch in NRC/NRO/DLSE
CIRES	Cooperative Institute for Research in Environmental Sciences
CL	confidence level
CL-ML	homogeneous silty clay soil
CMC	Canadian Meteorological Center forecasts
CMIP5	Coupled Model Intercomparison Project Phase 5
CMORPH / C-MORPH	Climate Prediction Center Morphing Technique
CNE	Romania Consiliul National al Elevilor
CNSC	Canadian Nuclear Safety Commission
CO	Colorado
CoCoRaHS	Community Collaborative Rain, Hail & Snow Network (NWS)
COE	U.S. Army Corps of Engineers (see also USACE)
COL	combined license
COLA	combined license application
COM-SECY	NRC staff requests to the Commission for guidance
CONUS	Continental United States
COOP	Cooperative Observer Network (NWS)

COR	contracting officer’s representative
CPC	Climate Prediction Center (NOAA)
CPFs	cumulative probability functions
CR	comprehensive review
CRA	computational risk assessment
CRB	Concerns Resolution Branch in NRC/OE
CRL	coastal reference location
CRPS	continuous ranked probability score
CSNI	Committee on the Safety of Nuclear Installations
CSRB	Criticality, Shielding & Risk Assessment Branch in NRC/NMSS/DSFM
CSSR	Climate Science Special Report (by the U.S. Global Change Research Program)
CSTORM	Coastal Storm Modeling System
CTA Note	note to Commissioners’ Assistants
CTXS	Coastal Texas Study
C_V	coefficient of variation
CZ	capture zone
DC	District of Columbia
DAD	depth-area-duration
DAMBRK	Dam Break Flood Forecasting Model (NWS)
DAR	Division of Advanced Reactors in NRC/NRO
DayMet	daily surface weather and climatological summaries
dBz	decibel relative to z, or measure of reflectivity of radar
DCIP	Division of Construction Inspection and Operational Programs in NRC/NRO
DDF	depth-duration-frequency curve
DDM	data-driven methodology
DDST	database of daily storm types
DE	Division of Engineering in NRC/RES
DHSVM	distributed hydrology soil vegetation model, supported by University of Washington
DIRS	Division of Inspection and Regional Support in NRC/NRR
DJF	December, January, February
DLBreach	Dam/Levee Breach model developed by Weiming Wu, Clarkson University
DLSE	Division of Licensing, Siting, and Environmental Analysis in NRC/NRO

DOE	U.S. Department of Energy
Dp	pressure deficit
DPI	power dissipation index
DPR	Division of Preparedness and Response in NRC/NSIR
DPR	Dual Frequency Precipitation Radar
DQO	data quality objective
DRA	Division of Risk Assessment in NRC/NRR
DRA	Division of Risk Analysis in NRC/RES
DREAM	Differential Evolution Adaptive Metropolis
DRP	Division of Reactor Projects in NRC/R-I
DRS	Division of Reactor Safety In NRC/R-I and R-IV
DSA	Division of Systems Analysis in NRC/RES
DSEA	Division of Site Safety and Environmental Analysis, formerly in NRC/NRO, now in DLSE
DSFM	Division of Spent Fuel Management in NRC/NMSS
DSI3240	NCEI hourly precipitation data
DSMS	Dam Safety Modification Study
DSMS	digital surface models
DSPC	USACE Dam Safety Production Center
DSRA	Division of Safety Systems, Risk Assessment and Advanced Reactors in NRC/NRO (merged into DAR)
DSS	Division of Safety Systems in NRC/NRR
DSS	Hydrologic Engineering Center Data Storage System
DTWD	doubly truncated Weibull distribution
DUWP	Division of Decommissioning, Uranium Recovery, and Waste Programs in NRC/NMSS
DWOPER	Operational Dynamic Wave Model (NWS)
dy	day
EAD	expected annual damage
EB2/EB3	Engineering Branch 2/3 in NRC/R-IV/DRS
EBTRK	Tropical Cyclone Extended Best Track Dataset
EC	Eddy Covariance Method
EC	environmental condition
ECC	ensemble copula coupling
ECCS	emergency core cooling systems pump

ECs	environmental conditions
EDF	Électricité de France
EDG	emergency diesel generator
EF	environmental factor
EFW	emergency feedwater
EGU	European Geophysical Union
EHCOE	NRC External Hazard Center of Expertise
EHID	External Hazard Information Digest
EIRL	equivalent independent record length
EIS	environmental impact statement
EKF	Epanechikov kernel function
EMA	expected moments algorithm
EMCWF	European Centre for Medium-Range Weather Forecasts
EMDR	eastern main development region (for hurricanes)
EMRALD	Event Model Risk Assessment using Linked Diagrams
ENSI	Swiss Federal Nuclear Safety Inspectorate
ENSO	El Niño Southern Oscillation
EPA	U.S. Environmental Protection Agency
EPIP	emergency plan implementing procedure
EPRI	Electric Power Research Institute
ER	engineering regulation (USACE)
ERA-40	European ECMWF reanalysis dataset
ERB	Environmental Review Branch in NRC/NMSS/FCSE
ERDC	Engineer Research and Development Center (USACE)
ERL	equivalent record length
ESCC	Environmental and Siting Consensus Committee (ANS)
ESEB	Structural Engineering Branch in NRC/RES/DE
ESEWG	Extreme Storm Events Work Group (ACWI/SOH)
ESP	early site permit
ESRI	Environmental Systems Research Institute
ESRL	Earth Systems Research Lab (NOAA/OAR)
EST	Eastern Standard Time
EST	empirical simulation technique
ESTP	enhanced storm transposition procedure

ET	event tree
ET	evapotranspiration
ET/FT	event tree/fault tree
ETC	extratropical cyclone
EUS	eastern United States
EV4	extreme value with four parameters distribution function
EVA	extreme value analysis
EVT	extreme value theory
EXHB	External Hazards Branch in NRC/NRO/DLSE
Exp	experimental
f	annual probability of failure (USBR, USACE)
F1, F5	tornado strengths on the Fujita scale
FA	frequency analysis
FADSU	fluvial activity database of the Southeastern United States
FAQ	frequently asked question
FAST	Fourier Analysis Sensitivity Test
FBPS	flood barrier penetration seal
FBS	flood barrier system
FCM	flood-causing mechanism
FCSE	Division of Fuel Cycle Safety, Safeguards & Environmental Review in NRC/NMSS
FD	final design
FDC	flood design category (DOE terminology)
FEMA	Federal Emergency Management Agency
FERC	Federal Energy Regulatory Commission
FFA	flood frequency analysis
FFC	flood frequency curve
FHRR	flood hazard reevaluation report
FITAG	Flooding Issues Technical Advisory Group
FL	Florida
FLDFRQ3	U.S. Bureau of Reclamation flood frequency analysis tool
FLDWAV	flood wave model (NWS)
FLEX	diverse and flexible mitigation strategies
Flike	extreme value analysis package developed University of Newcastle, Australia

FLO-2D	two-dimensional commercial flood model
FM Approvals	Testing and Certification Services Laboratories, originally Factory Mutual Laboratories
f-N	annual probability of failure vs. average life loss, N
FOR	peak flood of record
FPM	flood protection and mitigation
FPS	flood penetration seal
FRA	Flood Risk Analysis Compute Option in HEC-WAT
FRM	Fire Risk Management, Inc.
FSAR	final safety analysis report
FSC	flood-significant component
FSG	FLEX support guidelines
FSP	flood seal for penetrations
FT	fault tree
ft	foot
FXHAB	Fire and External Hazards Analysis Branch in NRC/RES/DRA
FY	fiscal year
G&G	geology and geotechnical engineering
GA	generic action
GCHA	Deputy General Counsel for Hearings and Administration in NRC/OGC
GCM	Global Climate Model
GCRP	U.S. Global Change Research Program
GCRPS	Deputy General Counsel for Rulemaking and Policy Support in NRC/OGC
GEFS	Global Ensemble Forecasting System
GeoClaw	routines from Clawpack-5 (“Conservation Laws Package”) that are specialized to depth-averaged geophysical flows
GEO-IR	Geostationary Satellites—InfraRed Imagery
GEV	generalized extreme value
GFDL	Geophysical Fluid Dynamics Lab (NOAA)
GFS	Global Forecast System
GHCN	Global Historical Climatology Network
GHCND	Global Historical Climatology Network-Daily
GIS	geographic information system
GISS	Goddard Institute for Space Studies (NASA)

GKF	Gaussian Kernel Function
GL	generic letter
GLO	generalized logistic distribution
GLRCM	Great Lakes Regional Climate Model
GLUE	generalized likelihood uncertainty estimation
GMAO	Global Modeling and Assimilation Office (NASA)
GMC	ground motion characterization
GMD	geoscientific model development
GMI	GPM microwave imager
GMSL	global mean sea level
GNO	generalized normal distribution
GoF	goodness-of-fit
GPA/GPD	generalized Pareto distribution
GPCP SG	Global Precipitation Climatology Project—Satellite Gauge
GPLLJ	Great Plains lower level jet
GPM	Gaussian process metamodel
GPM	global precipitation measurement
GPO	generalized Pareto distribution
GPROF	Goddard profile algorithm
GRADEX	rainfall-based flood frequency distribution method
Grizzly	simulated component aging and damage evolution events RISMC tool
GRL	Geophysical Research Letters
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit—Global Research for Safety
GSA	global sensitivity analysis
GSFC	Goddard Space Flight Center
GSI	generic safety issue
GUI	graphical user interface
GW-GC	Well-graded gravel with clay and sand
GZA	a multidisciplinary consulting firm
h	second shape parameter of four-parameter Kappa distribution
h/hr	hour
H&H	hydraulics and hydrology
HAMC	hydraulic model characterization

HBV	rainfall runoff model Hydrologiska Byråns Vattenbalansalvdening, supported by the Swedish Meteorological and Hydrological Institute
HCA	hierarchical clustering analysis
HCTISN	Supreme Committee for Transparency and Information on Nuclear Safety (France)
HCW	hazardous convective weather
HDSC	NOAA/NWS/OWP Hydrometeorological Design Studies Center
HEC	Hydrologic Engineering Center, part of USACE/Institute for Water Resources
HEC-1	see HEC-HMS
HEC-FIA	Hydrologic Engineering Center Flood Impact Analysis Software
HEC-HMS	Hydrologic Modeling System
HEC-LifeSim	Hydrologic Engineering Center life loss and direct damage estimation software
HEC-MetVue	Hydrologic Engineering Center Meteorological Visualization Utility Engine
HEC-RAS	Hydrologic Engineering Center River Analysis System
HEC-ResSim	Hydrologic Engineering Center Reservoir System Simulation
HEC-SSP	Hydrologic Engineering Center Statistical Software Package
HEC-WAT	Hydrologic Engineering Center Watershed Analysis Tool
HEP	human error probability
HF	human factors
HFRB	Human Factors and Reliability Branch in NRC/RES/DRA
HHA	hydrologic hazard analysis
HHC	hydrologic hazard curve
HI	Hawaii
HLR	high-level requirement
HLWFCNS	Assistant General Counsel for High-Level Waste, Fuel Cycle and Nuclear Security in NRC/OGC/GCRPS
HMB	Hazard Management Branch in NRC/NRR/JLD, realigned
HMC	hydraulic/hydrologic model characterization
HMR	NOAA/NWS Hydrometeorological Report
HMS	hydrologic modeling system
HOMC	hydrologic model characterization
hPa	hectopascals (unit of pressure)

HR	homogenous region
HRA	human reliability analysis
HRL	Hydrologic Research Lab, University of California at Davis
HRRR	NOAA High-Resolution Rapid Refresh Model
HRRs	Fukushima Hazard Reevaluation Reports (EPRI term)
HRU	hydrologic runoff unit approach
HUC	hydrologic unit code for watershed (USGS)
HUNTER	human actions RISMC tool
HURDAT	National Hurricane Centers HURricane DATabases
Hz	hertz (1 cycle/second)
IA	integrated assessment
IA	Iowa
IAEA	International Atomic Energy Agency
IBTrACS	International Best Track Archive for Climate Stewardship
IC	initial condition
ICOLD	International Commission on Large Dams
ID	information digest
IDF	intensity-duration frequency curve
IDF	inflow design flood
IE	initiating event
IEF	initiating event frequency
IES	Dam Safety Issue Evaluation Studies
IHDM	Institute of Hydrology Distributed Model, United Kingdom
IID	independent and identically distributed
IL	Illinois
IMERG	Integrated Multi-satellitE Retrievals for GPM
IMPRINT	Improved Performance Research Integration Tool
in	inch
IN	information notice
INES	International Nuclear and Radiological Event Scale
INL	Idaho National Laboratory
IPCC	Intergovernmental Panel on Climate Change
IPE	individual plant examination
IPEEE	individual plant examination for external events

IPET	Interagency Performance Evaluation Taskforce for the Performance Evaluation of the New Orleans and Southeast Louisiana Hurricane Protection System
IPWG	International Precipitation Working Group
IR	infrared
IR	inspection report
IRIB	Reactor Inspection Branch in NRC/NRR/DIRS
IRP	Integrated Research Projects (DOE)
IRSN	Institut de Radioprotection et de Sûreté Nucléaire (France's Radioprotection and Nuclear Safety Institute)
ISG	interim staff guidance
ISI	inservice inspection
ISR	interim staff response
IT	information technology
IVT	integrated vapor transport
IWR	USACE Institute for Water Resources
IWVT	integrated water vapor tendency
J	joule
JJA	June, July, August
JLD	Japan Lesson-learned Directorate or Division in NRC/NRR, realigned
JPA	Joint Powers Authority (FEMA Region II)
JPA	joint probability analysis
JPM	joint probability method
JPM-OS	Joint Probability Method with Optimal Sampling
K	degrees Kelvin
KAERI	Korea Atomic Energy Research Institute
KAP	Kappa distribution
k_d	erodibility coefficient
kg	kilogram
kHz	kilohertz (1000 cycles/second)
km	kilometer
KS	Kansas
LA	Louisiana
LACPR	Louisiana Coastal Protection and Restoration Study
LAR	license amendment request

L-C_v	coefficient of L-variation
LEO	low earth orbit
LER	licensee event report
LERF	large early release frequency
LIA	Little Ice Age
LiDAR	light imaging, detection and ranging; surveying method using reflected pulsed light to measure distance
LIP	local intense precipitation
LMI	lifetime maximum intensity
LMOM / LMR	L-moment
LN4	Slade-type four parameter lognormal distribution function
LOCA	localized constructed analog
LOCA	loss-of-coolant accident
LOOP	loss of offsite power event
LOUHS	loss of ultimate heat sink event
LPIII / LP-III, LP3	Log Pearson Type III distribution
LS	leading stratiform
LS	local storm
LSHR	late secondary heat removal
LTWD	Left-truncated Weibull distribution
LULC	land use and land cover
LWR	light-water reactor
LWRS	Light-Water Reactor Sustainability Program
m	meter
MA	Massachusetts
MA	manual action
MAAP	coupling accident conditions RISMC tool
MAE	mean absolute error
MAM	March, April, May
MAP	mean annual precipitation
MASTODON	structural dynamics, stochastic nonlinear soil-structure interaction in a risk framework RISMC tool
mb	millibar
MCA	medieval climate anomaly
MCC	mesoscale convective complex

MCI	Monte Carlo integration
MCLC	Monte Carlo Life-Cycle
MCMC	Markov chain Monte Carlo method
MCRAM	streamflow volume stochastic modeling
MCS	mesoscale convective system
MCS	Monte Carlo simulation
MCTA	Behrangi Multisatellite CloudSat TRMM Aqua Product
MD	Maryland
MDL	Meteorological Development Laboratory (NWS)
MDR	Main Development Region (for hurricanes)
MDT	Methodology Development Team
MEC	mesoscale storm with embedded convection
MEOW	Maximum Envelopes of Water
MetStorm	storm analysis software by MetStat, second generation of SPAS
MGD	meta-Gaussian distribution
MGS Engineering	engineering consultants
MHS	microwave humidity sounder
MIKE SHE/ MIKE 21	integrated hydrological modeling system
MLC	mid-latitude cyclone
MLE	maximum likelihood estimation
mm	millimeter
MM5	fifth-generation Penn State/NCAR mesoscale model
MMC	mesh-based Monte Carlo method
MMC	meteorological model characterization
MMF	multimechanism flood
MMP	mean monthly precipitation
MN	Minnesota
MO	Missouri
Mode 3	Reactor Operation Mode: Hot Standby
Mode 4	Reactor Operation Mode: Hot Shutdown
Mode 5	Reactor Operation Mode: Cold Shutdown
MOM	Maximum of MEOWs
MOU	memorandum of understanding
MPE	multisensor precipitation estimates

mph	miles per hour
MPS	maximum product of spacings
MRMS	Multi-Radar Multi-Sensor project (NOAA/NSSL)
MS	Mississippi
MSA	mitigating strategies assessment
MSFHI	mitigating strategies flood hazard information
MSL	mean sea level
MSWEP	multisource weighted-ensemble precipitation dataset
MVGC	multivariable Gaussian copula
MVGD	multivariable Gaussian distribution
MVTC	multivariable student's t copula
N	average life loss (USBR, USACE)
NA14	NOAA National Atlas 14
NACCS	North Atlantic Coast Comprehensive Study
NAEFS	North American Ensemble Forecasting System
NAIP	National Agricultural Imagery Program
NAM-WRF	North American Mesoscale Model—WRF
NAO	North Atlantic Oscillation
NARCCAP	North American Regional Climate Change Assessment Program
NARR	North American Regional Reanalysis (NOAA)
NARSIS	European Research Project New Approach to Reactor Safety Improvements
NASA	National Aeronautics and Space Administration
NAVD88	North American Vertical Datum of 1988
NBS	net basin scale
NCA3/NCA4	U.S. Global Change Research Program Third/Fourth National Climate Assessment
NCAR	National Center for Atmospheric Research
NCEI	National Centers for Environmental Information
NCEP	National Centers for Environmental Prediction (NOAA)
ND	North Dakota
NDFD	National Digital Forecast Database (NWS)
NDSEV	number of days with severe thunderstorm environments
NE	Nebraska
NEA	Nuclear Energy Agency

NEB	nonexceedance bounds
NEI	Nuclear Energy Institute
NESDIS	NOAA National Environmental Satellite, Data, and Information Service
NEUTRINO	a general-purpose simulation and visualization environment including an SPH solver
NEXRAD	next-generation radar
NHC	National Hurricane Center
NI DAQ	National Instruments Data Acquisition Software
NID	National Inventory of Dams
NIOSH	National Institute for Occupational Safety and Health
NLDAS	North American Land Data Assimilation System
nm	nautical miles
NM	New Mexico
NMSS	NRC Office of Nuclear Material Safety and Safeguards
NOAA	National Oceanic and Atmospheric Administration
NOED	notice of enforcement discretion
NPDP	National Performance of Dams Program
NPH	Natural Phenomena Hazards Program (DOE)
NPP	nuclear power plant
NPS	National Park Service
NRC	U.S. Nuclear Regulatory Commission
NRCS	Natural Resources Conservation Service
NRO	NRC Office of New Reactors
NRR	NCEP-NCAR Reanalysis
NRR	NRC Office of Nuclear Reactor Regulation
NSE	Nash-Sutcliffe model efficiency coefficient
NSIAC	Nuclear Strategic Issues Advisory Committee
NSIR	NRC Office of Nuclear Security and Incident Response
NSSL	National Severe Storms Laboratory (NOAA)
NSTC	National Science and Technology Council
NTTF	Near-Term Task Force
NUREG	NRC technical report designation
NUVIA	a subsidiary of Vinci Construction Group, offering expertise in services and technology supporting safety performance in nuclear facilities
NWS	National Weather Service

NY	New York
OAR	NOAA Office of Oceanic and Atmospheric Research
OE	NRC Office of Enforcement
OECD	Organization for Economic Co-operation and Development
OEDO	NRC Office of the Executive Director for Operations
OGC	NRC Office of the General Counsel
OHC	ocean heat content
OK	Oklahoma
OR	Oregon
ORNL	Oak Ridge National Laboratory
OSL	optically stimulated luminescence
OTC	once-through cooling
OWI	Ocean Wind Inc.
OWP	NOAA/NWS Office of Water Prediction
P	present
P/PET	precipitation over PET ratio, aridity
Pa	pascal
PB1	Branch 1 in NRC/R-I/DRP
PBL	planetary boundary layer
PCA	principal component analysis
PCHA	probabilistic coastal hazard assessment
PCMQ	Predictive Capability Maturity Quantification
PCMQBN	Predictive Capability Maturity Quantification by Bayesian Net
PD	performance demand
PDF	probability density function
PDF	performance degradation factor
PDS	partial-duration series
PE3	Pearson Type III distribution
PeakFQ	USGS flood frequency analysis software tool based on Bulletin 17C
PERSIANN-CCS	Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks—Cloud Classification System (University of California at Irvine Precipitation Algorithm)
PERT	program evaluation review technique
PET	potential evapotranspiration
P-ETSS	Probabilistic Extra-Tropical Storm Surge Model

PF	paleoflood
PF/P-F	precipitation frequency
PFAR	precipitation field area ratio
PFHA	probabilistic flood hazard assessment
PFM	potential failure mode
PI	principal investigator
P-I	pressure-impulse curve
PIF	performance influencing factor
PILF	potentially influential low flood
PM	project manager
PMDA	Program Management, Policy Development & Analysis in NRC/RES
PMF	probable maximum flood
PMH	probable maximum hurricane
PMP	probable maximum precipitation
PMW	passive microwave
PN	product number
PNAS	Proceedings of the National Academy of Sciences of the United States of America
PNNL	Pacific Northwest National Laboratory
POANHI	Process for Ongoing Assessment of Natural Hazard Information
POB	Regulatory Policy and Oversight Branch in NRC/NSIR/DPR
POR	period of record
PPRP	participatory peer review panel
PPS	Precipitation Processing System
PR	Puerto Rico
PRA	probabilistic risk assessment
PRAB	Probabilistic Risk Assessment Branch in NRC/RES/DRA
PRB	Performance and Reliability Branch in NRC/RES/DRA
PRISM	a gridded dataset developed through a partnership between the NRCS National Water and Climate Center and the PRISM Climate Group at Oregon State University, developers of PRISM (the Parameter-elevation Regressions on Independent Slopes Model)
PRMS	USGS Precipitation Runoff Modelling System
Prométhée	IRSN software based on PROMETHEE, the Preference Ranking Organization METhod for Enrichment Evaluation
PRPS	Precipitation Retrieval Profiles Scheme

PS	parallel stratiform
PSA	probabilistic safety assessment, common term for PRA in other countries
PSD	Physical Sciences Division in NOAA/OAR/ESRL
PSF	performance shaping factor
psf	pounds per square foot
PSHA	probabilistic seismic hazard assessment
PSI	paleostage indicators
PSSHA	probabilistic storm surge hazard assessment
P-Surge	probabilistic tropical cyclone storm surge model
PTI	project technical integrator
PVC	polyvinyl chloride
Pw/PW	precipitable water
PWR	pressurized-water reactor
Q	quarter
QA	quality assurance
QC	quality control
QI	Quality Index
QPE	quantitative precipitation estimates
QPF	quantitative precipitation forecast
R	a statistical package
R 2.1	NTTF Report Recommendation 2.1
R&D	research and development
R2	coefficient of determination
RAM	regional atmospheric model
RASP	Risk Assessment of Operational Events Handbook
RAVEN	risk analysis in a virtual environment probabilistic scenario evolution RISMC tool
RC	reinforced concrete
RCP (4.5, 8.5)	representative concentration pathways
RELAP-7	reactor excursion and leak analysis program transient conditions RISMC tool
RENV	Environmental Technical Support Branch in NRC/NRO/DLSE
REOF	rotated empirical orthogonal function
RES	NRC Office of Nuclear Regulatory Research

RF	riverine flooding
RFA	regional frequency analysis
RFC	River Forecast Center (NWS)
RG	regulatory guide
RGB	red, green, and blue imagery (NAIP)
RGB-IF	red, green, blue, and infrared imagery (NAIP)
RGC	regional growth curve
RGGIB	Regulatory Guidance and Generic Issues Branch in NRC/RES/DE
RGS	Geosciences and Geotechnical Engineering Branches now in NRC/NRO/DLSE, formerly in NRC/NRO/DSEA
RHM	Hydrology and Meteorology Branch formerly in NRC/NRO/DSEA
RI	Rhode Island
R-I, R-II, R-III, R-IV	NRC Regions I, II, III, IV
RIC	Regulatory Information Conference, NRC
RIDM	risk-informed decisionmaking
RILIT	Risk-Informed Licensing Initiative Team in NRC/NRR/DRA/APLB
RISMC	risk information safety margin characterization
R_{max}	radius to maximum winds
RMB	Renewals and Materials Branch in NRC/NMSS/DSFM
RMC	USACE Risk Management Center
RMSD	root-mean-square deviation
RMSE	root mean square error
ROM	reduce order modeling
ROP	Reactor Oversight Process
RORB-MC	an interactive runoff and streamflow routing program
RPAC	formerly in NRC/NRO/DSEA
RRTM	Rapid Radiative Transfer Model Code in WRF
RRTMS	RRTM with GCM application
RS	response surface
RTI	an independent, nonprofit institute
RV	return values
SA	storage area
SACCS	South Atlantic Coastal Comprehensive Study
SAPHIR	Sounding for Probing Vertical Profiles of Humidity

SAPHIRE	Systems Analysis Programs for Hands-on Integrated Reliability Evaluations
SBDFA	simulation-based dynamic flooding analysis framework
SBO	station blackout
SBS	simulation-based scaling
SC	safety category (ANS 58.16-2014 term)
SC	South Carolina
SCAN	Soil Climate Analysis Network
SCRAM	immediate shutdown of nuclear reactor
SCS	curve number method
SD	standard deviation
SDC	shutdown cooling
SDP	significance determination process
SDR	Subcommittee on Disaster Reduction
SECY	written issues paper the NRC staff submits to the Commission
SEFM	Stochastic Event-Based Rainfall-Runoff Model
SER	safety evaluation report
SGSEB	Structural, Geotechnical and Seismic Engineering Branch in NRC/RES/DE
SHAC-F	Structured Hazard Assessment Committee Process for Flooding
SHE	Systém Hydrologique Européan
SITES	model that uses headcut erodibility index by USDA-ARS and University of Kansas "Earthen/Vegetated Auxiliary Spillway Erosion Prediction for Dams"
SLC	sea level change
SLOSH	Sea Lake and Overland Surges from Hurricanes (NWS model)
SLR	sea level rise
SMR	small modular reactor
SNOTEL	snow telemetry
SNR	signal-to-noise ratio
SOH	Subcommittee on Hydrology
SOM	self-organizing map
SON	September, October, November
SOP	standard operating pressure
SPAR	standardized plant analysis risk
SPAS	Storm Precipitation Analysis System (MetStat, Inc.)

SPH	smoothed-particle hydrodynamics
SPRA	PRA and Severe Accidents Branch in NRC/NRO/DESR (formerly in DSRA)
SRA	senior reactor analyst
SRES A2	NARCCAP A2 emission scenario
SRH2D/SRH-2D	USBR Sedimentation and River Hydraulics—Two-Dimensional model
SRM	staff requirements memorandum
SRP	standard review plan
SRR	storm recurrence rate
SSAI	Science Systems and Applications, Inc.
SSC	structure, system, and component
SSHAC	Senior Seismic Hazard Assessment Committee
SSM	Swedish Radiation Safety Authority (Strål säkerhets mydigheten)
SSMI	Special Sensor Microwave Imager
SSMIS	Special Sensor Microwave Imager/Sounder
SSPMP	site-specific probable maximum precipitation
SST	sea surface temperature
SST	stochastic simulation technique
SST	stochastic storm transposition
SSURGO	soil survey geographic database
ST4 or Stage IV	precipitation information from multisensor (radar and gauges) precipitation analysis
STEnv	severe thunderstorm environment
STM	stochastic track method
StormSIm	stochastic storm simulation system
STSB	Technical Specifications Branch in NRC/NRR/DSS
STUK	Finland Radiation and Nuclear Safety Authority
STWAVE	STEady-state spectral WAVE model
SÚJB	Czech Republic State Office for Nuclear Safety
SWAN	Simulation Waves Nearshore Model
SWE	snow-water equivalent
SWL	still water level
SWMM	EPA Storm Water Management Model
SWT	Schaefer-Wallis-Taylor Climate Region Method
TAG	EPRI Technical Assessment Guide

TC	tropical cyclone
TCI	TRMM Combined Instrument
Td	daily temperature
TDF	transformed extreme value type 1 distribution function (four parameter)
TDI	technically defensible interpretations
TELEMAC	two-dimensional hydraulic model
TELEMAC 2D	a suite of finite element computer programs owned by the Laboratoire National d'Hydraulique et Environnement (LNHE), part of the R&D group of Électricité de France
T-H	thermohydraulic
TI	technical integration
TI	technology innovation project
TL	training line
TMI	Three Mile Island
TMI	TRMM Microwave Imager
TMPA	TRMM Multisatellite Precipitation Analysis
TN	Tennessee
TOPMODEL	two-dimensional distributed watershed model by Keith Beven, Lancaster University
TOVS	Television-Infrared Observation Satellite (TIROS) Operational Vertical Sounder
TP-#	Test Pit #
TP-29	U.S. Weather Bureau Technical Paper No. 29
TP-40	Technical Paper No. 40, “Rainfall Frequency Atlas of the U.S.,” 1961
TR	USACE technical report
TREX	two-dimensional, runoff, erosion, and export model
TRMM	Tropical Rainfall Measuring Mission
TRVW	Tennessee River Valley Watershed
TS	technical specification
TS	trailing stratiform
TSR	tropical-storm remnant
TUFLOW	two-dimensional hydraulic model
TVA	Tennessee Valley Authority
TX	Texas
U.S. or US	United States
UA	uncertainty analysis

UC	University of California
UH	unit hydrograph
UKF	uniform kernel function
UKMET	medium-range (3- to 7-day) numerical weather prediction model operated by the United Kingdom METeorological Agency
UL	Underwriters Laboratories
UMD	University of Maryland
UNR	user need request
UQ	uncertainty quantification
URMDB	Uranium Recovery and Materials Decommissioning Branch in NRC/NMSS/DUWP
USACE	U.S. Army Corps of Engineers (see also COE)
USACE-NWD	USACE NorthWest Division
USBR	U.S. Bureau of Reclamation
USDA	U.S. Department of Agriculture
USDA-ARS	United State Department of Agriculture—Agricultural Research Service
USFWS	U.S. Fish and Wildlife Service
USGS	United States Geological Survey
UTC	coordinated universal time
VA	Virginia
VDB	validation database
VDMS	Validation Data Management System
VDP	validation data planning
VIC	Variable Infiltration Capacity model
VL-AEP	very low annual exceedance probability
W	watt
WAK	Wakeby distribution
WASH-1400	Reactor Safety Study: An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants [NUREG-75/014 (WASH-1400)]
WB	U.S. Weather Bureau
WBT	wet bulb temperature
WEI	Weibull distribution
WGEV	Working Group on External Events
WGI	Working Group I
WI	Wisconsin

WinDamC	USDA/NRCS model for estimating erosion of earthen embankments and auxiliary spillways of dams
WL	water level
WMO	World Meteorological Organization
WRB	Willamette River Basin
WRF	Weather Research and Forecasting model
WRR	Water Resources Research (journal)
WSEL / WSL	water surface elevation
WSM6	WRF Single-Moment 6-Class Microphysics Scheme
WSP	USGS Water Supply Paper
XF	external flooding
XFEL	external flood equipment list
XFOAL	external flood operation action list
XFPRA	external flooding PRA
yr	year
yrBP	years before present
Z	Zulu time, equivalent to UTC

INTRODUCTION

Background

The NRC is conducting a multiyear, multi-project Probabilistic Flood Hazard Assessment (PFHA) Research Program. It initiated this research in response to staff recognition of a lack of guidance for conducting PFHAs at nuclear facilities that required staff and licensees to use highly conservative deterministic methods in regulatory applications. The staff described the objective, research themes, and specific research topics in the "Probabilistic Flood Hazard Assessment Research Plan," Version 2014-10-23, provided to the Commission in November 2014 (ADAMS Accession Nos. ML14318A070 and ML14296A442). The PFHA Research Plan was endorsed in a joint user need request by the NRC Office of New Reactors and Office of Nuclear Reactor Regulation (UNR NRO-2015-002, ADAMS Accession No. ML15124A707). This program is designed to support the development of regulatory tools (e.g., regulatory guidance, standard review plans) for permitting new nuclear sites, licensing new nuclear facilities, and overseeing operating facilities. Specific uses of flooding hazard estimates (i.e., flood elevations and associated affects) include flood-resistant design for structures, systems, and components (SSCs) important to safety and advanced planning and evaluation of flood protection procedures and mitigation.

The lack of risk-informed guidance with respect to flooding hazards and flood fragility of SSCs constitutes a significant gap in the NRC's risk-informed, performance-based regulatory approach to the assessment of hazards and potential safety consequences for commercial nuclear facilities. The probabilistic technical basis developed will provide a risk-informed approach for improved guidance and tools to give staff and licensees greater flexibility in evaluating flooding hazards and potential impacts to SSCs in the oversight of operating facilities (e.g., license amendment requests, significance determination processes (SDPs), notices of enforcement discretion (NOEDs)) as well as licensing of new facilities (e.g., early site permit applications, combined license (COL) applications), including proposed small modular reactors (SMRs) and advanced reactors. This methodology will give staff more flexibility in assessing flood hazards at nuclear facilities so the staff will not have to rely on the use of the current deterministic methods, which can be overly conservative in some cases.

The main focus areas of the PFHA Research Program are to (1) leverage available frequency information on flooding hazards at operating nuclear facilities and develop guidance on its use, (2) develop and demonstrate a PFHA framework for flood hazard curve estimation, (3) assess and evaluate application of improved mechanistic and probabilistic modeling techniques for key flood-generating processes and flooding scenarios, (4) assess potential impacts of dynamic and nonstationary processes on flood hazard assessments and flood protection at nuclear facilities, and (5) assess and evaluate methods for quantifying reliability of flood protection and plant response to flooding events. Workshop organizers used these focus areas to develop technical session topics for the workshop.

Workshop Objectives

The Annual PFHA Research Workshops serve multiple objectives: (1) inform and solicit feedback from internal NRC stakeholders, partner Federal agencies, industry, and the public about PFHA research being conducted by the NRC Office of Nuclear Regulatory Research (RES), (2) inform internal and external stakeholders about RES research collaborations with Federal agencies, the Electric Power Research Institute (EPRI) and the French Institute for Radiological and Nuclear

Security (IRNS) and (3) provide a forum for presentation and discussion of notable domestic and international PFHA research activities.

Workshop Scope

Scope of the workshop presentations and discussions included:

- Current and future climate influences on flooding processes
- Significant precipitation and flooding events
- Statistical and mechanistic modeling approaches for precipitation, riverine flooding, and coastal flooding processes
- Probabilistic flood hazard assessment frameworks
- Reliability of flood protection and mitigation features and procedures
- External flooding probabilistic risk assessment

Summary of Proceedings

These proceedings transmit the agenda, abstracts, and slides from presentations and posters presented, and chronicle the question and answer sessions and panel discussions held, at the U.S. Nuclear Regulatory Commission's (NRC's) Annual Probabilistic Flood Hazard Assessment (PFHA) Research Workshops, which take place approximately annually at NRC Headquarters in Rockville, MD. The first four workshops took place as follows:

- 1st Annual NRC PFHA Research Workshop, October 14–15, 2015
- 2nd Annual NRC PFHA Research Workshop, January 23–25, 2017 (Agencywide Documents Access and Management System (ADAMS) Accession No. ML17040A626)
- 3rd Annual NRC PFHA Research Workshop, December 4–5, 2017 (ADAMS Accession No. ML17355A071)
- 4th Annual NRC PFHA Research Workshop, April 30–May 2. 2019 (ADAMS Accession No. ML19156A446)

These proceedings include presentation abstracts and slides and a summary of the question and answer sessions. The first workshop was limited to NRC technical staff and management, NRC contractors, and staff from other Federal agencies. The three workshops that followed were meetings attended by members of the public; NRC technical staff, management, and contractors; and staff from other Federal agencies. Public attendees over the course of the workshops included industry groups, industry members, consultants, independent laboratories, academic institutions, and the press. Members of the public were invited to speak at the workshops. The fourth workshop included more invited speakers from the public than from the NRC and the NRC's contractors.

The proceedings for the second through fourth workshops include all presentation abstracts and slides and submitted posters and panelists' slides. Workshop organizers took notes and audio-recorded the question and answer sessions following each talk, during group panels, and during end-of-day question and answer session. Responses are not reproduced here verbatim and were generally from the presenter or co-authors. Descriptions of the panel discussions identify the speaker when possible. Questions were taken orally from attendees, on question cards, and over the telephone.

Related Workshops

An international workshop on PFHA took place on January 29–31, 2013. The workshop was devoted to sharing information on PFHAs for extreme events (i.e., annual exceedance probabilities (AEPs) much less than $2x10^{-3}$ per year) from the Federal community). The NRC issued the proceedings as NUREG/CP-302, "Proceedings of the Workshop on Probabilistic Flood Hazard Assessment (PFHA)," in October 2013 (ADAMS Accession No. ML13277A074).

3 THIRD ANNUAL NRC PROBABILISTIC FLOOD HAZARD ASSESSMENT RESEARCH WORKSHOP

3.1 Introduction

This chapter details the 3rd Annual NRC Probabilistic Flood Hazard Assessment (PFHA) Research Workshop held at the U.S. Nuclear Regulatory Commission (NRC) Headquarters in Rockville, MD, on December 4-5, 2017. These proceedings include abstracts for the presentations, the slides from the presentations themselves, and a summary of question and answer sessions. The workshop was a public meeting attended by members of the public; NRC technical staff, management, and contractors; and staff from other Federal agencies.

The workshop began with an introduction from Mike Weber, Director, NRC Office of Nuclear Regulatory Research (RES). Following the introduction, NRC RES and Electric Power Research Institute (EPRI) staff presented descriptions of their flooding research programs.

Following the introduction session, NRC and EPRI contractors and staff gave technical presentations and answered clarifying questions. Partner Federal agencies took part in two panel discussions on their PFHA and external PRA efforts. At the end of each day, participants had an opportunity to provide feedback and ask generic questions about research related to PFHA for nuclear facilities.

3.1.1 Organization of Conference Proceedings

Section 3.2 provides the agenda for this workshop. The program is also located at ADAMS Accession No. ML17355A081

Section 3.3 presents the proceedings from the workshop, including abstract, presentation slides, and summaries of the question and answer session for each of the technical sessions.

The summary document of session abstracts for the technical presentations can be viewed in the PFHA Research Workshop Program at ADAMS Accession No. ML17355A081. The complete workshop presentation package is available at ADAMS Accession No. ML17355A071.

Section 0is a summary of the proceedings and Section 0provides a list of the workshop attendees, including remote participants.

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3.2 Workshop Agenda (ADAMS Accession No. ML17355A081)

3rd Annual NRC Probabilistic Flood Hazard Assessment Research Workshop at NRC headquarters in Rockville, Maryland

AGENDA: MONDAY, DECEMBER 4, 2017

08:10 – 08:20 Welcome

Session 1A - Introduction

Session Chair: Meredith Carr, NRC/RES

08:20 – 08:30	Introduction *Mike Weber*, Director, Office of Nuclear Regulatory Research*	1A-1
08:30 – 09:00	NRC Flooding Research Program Overview *Joseph Kanney*, Meredith Carr, Tom Aird, Elena Yegorova, Mark Fuhrmann and Jacob Philip, NRC/RES*	1A-2
09:00 – 09:30	EPRI Flooding Research Program Overview *John Weglian*, Electric Power Research Institute (EPRI)*	1A-3

09:30 – 09:45 BREAK

Session 1B - Climate and Precipitation

Session Chair: Elena Yegorova, NRC/RES

09:45 – 10:15	Regional Climate Change Projections: Potential Impacts to Nuclear Facilities *L. Ruby Leung* and Rajiv Prasad, Pacific Northwest National Laboratory*	1B-1
10:15 – 10:45	Numerical Modeling of Local Intense Precipitation Processes *M. Levent Kavvas, Mathieu Mure-Ravaud* and Alain Dib* Hydrologic Research Laboratory, Department. Of Civil and Environmental Engineering, University of California, Davis*	1B-2
10:45 – 11:15	Research to Develop Guidance on Extreme Precipitation Estimates in Orographic Regions *Kathleen Holman^, Andrew Verdin and D. Keeney, U.S. Bureau of Reclamation, Technical Service Center, Flood Hydrology and Meteorology*	1B-3

**** denotes presenter, ^ denotes remote presenter***

Session 1C - Storm Surge

Session Chair: Joseph Kanney, NRC/RES

11:15 – 11:45	Quantification of Uncertainty in Probabilistic Storm Surge Models *Norberto C. Nadal-Caraballo, and Victor Gonzalez*, U.S. Army Engineer R&D Center, Coastal and Hydraulics Laboratory*	1C-1
11:45 – 12:15	Probabilistic Flood Hazard Assessment – Storm Surge *John Weglian*, EPRI*	1C-2
12:15 – 13:15	LUNCH	

Session 1D - Leveraging Available Flood Information

Session Chair: Nebiyu Tiruneh, NRC/NRO

13:15 – 13:45	Flood Frequency Analyses for Very Low Annual Exceedance Probabilities using Historic and Paleoflood Data, with Considerations for Nonstationary Systems *Karen Ryberg*, Kelsey Kolars and Julie Kiang, U.S. Geological Survey*	1D-1
13:45 – 14:15	Extending Frequency Analysis Beyond Current Consensus Limits *Keil Neff* and Joseph Wright, U.S. Bureau of Reclamation, Technical Service Center, Flood Hydrology & Meteorology*	1D-2
14:15 – 14:45	Development of External Hazard Information Digests for Operating NPP sites *Kellie Kvarfordt* and Curtis Smith, Idaho National Laboratory*	1D-3
14:45 – 15:00	BREAK	

Session 1E - Paleoflood Studies

Session Chair: Mark Fuhrmann, NRC/RES

15:00 – 15:30	Improving Flood Frequency Analysis with a Multi-Millennial Record of Extreme Floods on the Tennessee River near Chattanooga, TN *Tessa Harden*, Jim O'Connor and Mackenzie Keith, U.S. Geological Survey*	1E-1
15:30 – 16:00	Collection of Paleoflood Evidence *Lisa Davis*, University of Alabama and Gary Stinchcomb, Murray State University*	1E-2
16:00 – 16:30	Daily Wrap-up and Public Comments/Questions	
16:30 – 18:00	Posters (Session 1F), Session Chair: Tom Aird, NRC/RES	

Session 1F: Posters

Session Chair: Tom Aird, NRC/RES

Probability-Based Flow Modeling Using the Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS)

Brian Skahill, U.S. Army Corps of Engineers, Engineer Research and Development Center, Coastal and Hydraulics Laboratory

Reclamation's Paleoflood Database: Design, Structure and Application

Jeanne E. Godaire, Kurt Wille, and Ralph E. Klinger, U.S. Bureau of Reclamation, Technical Services Center

Late Holocene Paleofloods Along the Middle Tennessee River Valley

C. Lance Stewart and Gary E. Stinchcomb, Department of Geosciences and Watershed Studies Institute, Murray State University; Steven L. Forman, Department of Geology, Baylor University; Lisa Davis and Rachel Lombardi, Department of Geography, University of Alabama; Emily Blackaby, Owen Craven and William Hockaday, Department of Geology, Baylor University

A regional chronology of floods and river activity during the last 10,000 years in the Eastern U.S.

Lisa Davis and Rachel Lombardi, Department of Geography, University of Alabama; Gary Stinchcomb, Watershed Studies Institute, Murray State University; C. Lance Stewart, Department of Geosciences, Murray State University; Matthew D. Therrell, Department of Geography, University of Alabama; Matthew Gage, Office of Archeological Research, University of Alabama

Critical Review of State of Practice in Dam Risk Assessment

David Watson, Scott DeNeale, Brennan Smith, Shih-Chieh Kao, Oak Ridge National Laboratory (ORNL); Gregory Baecher, University of Maryland

Application of Point Precipitation Frequency Estimates to Watersheds

Shih-Chieh Kao and Scott DeNeale, Oak Ridge National Laboratory

Quantification of Uncertainty in Probabilistic Storm Surge Models

Norberto Nadal-Caraballo, Victor Gonzalez and Efrain Ramos-Santiago U.S. Army Corps of Engineers, Engineer Research and Development Center, Coastal and Hydraulics Laboratory

Modeling Plant Response to Flooding Events

Zhegang Ma, Curtis L. Smith and Steven R. Prescott, Idaho National Laboratory, Risk Assessment and Management Services; Ramprasad Sampath, Centroid PIC, Research and Development

Stratigraphic Records of Paleofloods, Geochronology and Hydraulic Modeling to Improve Flood Frequency Analysis

Tessa Harden, U.S. Geological Survey, Oregon Water Science Center

08:00 – 08:10	Day 2 Welcome	

Session 2A - Reliability of Flood Protection and Mitigation

Session Chair: Mehdi Reisi-Fard, NRC/NRR

08:10 – 08:40	Performance of Flood-Rated Penetration Seals *William (Mark) Cummings*, Fire Risk Management*	2A-1
08:40 – 09:10	EPRI Flood Protection Project Status *David Ziebell^ and John Weglian, EPRI*	2A-2
09:10 – 09:40	A Conceptual Framework to Assess Impacts of Environmental Conditions on Manual Actions for Flood Protection and Mitigation at Nuclear Power Plants *Rajiv Prasad*, Garill Coles, Angela Dalton, and Nancy Kohn, Pacific Northwest National Laboratory; Kristi Branch and Alvah Bittner, Bittner and Associates; R. Scott Taylor, Battelle*	2A-3
09:40 – 09:55	BREAK	
09:55 – 10:25	External Flooding PRA Walkdown Guidance *John Weglian*, EPRI*	2A-4
10:25 – 10:55	Erosion Testing of Zoned Rockfill Embankments *Tony Wahl^, U.S. Bureau of Reclamation*	2A-5

Session 2B - PFHA Frameworks

Session Chair: John Weglian, EPRI

10:55 – 11:25	A Framework for Inland Probabilistic Flood Hazard Assessments: Analysis of Extreme Snow Water Equivalent in Central New Hampshire *Brian Skahill* and Carrie Vuyovich, U.S. Army Corps of Engineers, Engineer Research and Development Center*	2B-1
11:25 – 11:55	Structured Hazard Assessment Committee Process for Flooding (SHAC-F) for Riverine Flooding *Rajiv Prasad* and Philip Meyer, Pacific Northwest National Laboratory; Kevin Coppersmith, Coppersmith Consulting*	2B-2
11:55 – 13:00	LUNCH	

Session 2C - Panel Discussions

13:00 – 14:20 Flood Hazard Assessment Research and Guidance Activities in Partner Agencies 2C-1
Session Chair: Joseph Kanney, NRC/RES
Panelists:

Norberto Nadal-Caraballo, U.S. Army Corps of Engineers, Engineer Research and Development Center
John England, U.S. Army Corps of Eng., Risk Management Center
Kenneth Fearon, Federal Energy Regulatory Commission, Office of Energy Projects, Division of Dam Safety and Inspections
Sharon Jasim-Hanif, Department of Energy, Office of Nuclear Safety
Gabriel Miller, Tennessee River Valley Authority, River Management Department

14:20 – 15:45 External Flooding Probabilistic Risk Assessment: Perspectives on Gaps and Challenges 2C-2
Session Chair: Fernando Ferrante, EPRI
Panelists:

John Weglian, EPRI
Zhegang Ma, Idaho National Laboratory
Ray Schneider, Westinghouse
Frances Pimentel and Victoria Anderson, Nuclear Energy Institute
Nathan Siu, NRC/RES
Christopher Cook, NRC/NRO

15:45 – 15:55 BREAK

Session 2D - Future Work at NRC and EPRI

Session Chair: Mark Fuhrmann, NRC/RES

15:55 – 16:15 Future Work in PFHA at EPRI 2D-1
John Weglian, EPRI*

16:15 – 16:35 Future Work in PFHA at NRC 2D-2
Joseph Kanney, Meredith Carr, Tom Aird, Elena Yegorova, Mark Fuhrmann and Jacob Philip, NRC/RES*

16:35 – 17:00 Final Wrap-up and Public Comments/Questions

3.3 Proceedings

3.3.1 Day 1: Session 1A - Introduction

Session Chair: Meredith Carr, NRC/RES/DRA/FXHAB

There are no abstracts for this introductory session.

3.3.1.1 Welcome Michael Weber, Director, Office of Nuclear Regulatory Research (Session 1A-1; ADAMS Accession No. ML17355A082)

Why PFHA Research?

- Address gap in Risk-Informed Regulatory Framework
  - Commission policy to use risk-informed approaches to the extent practical
  - Other external hazards (e.g., wind, seismic) are evaluated using probabilistic approaches and metrics.
  - Current regulatory basis wrt flooding hazards (Reg Guides, Standard Review Plan, etc.) is deterministic
- Recent experience has highlighted importance of risk-informing flood hazard assessment and consequence analysis
  - Flooding events at NPPs in U.S. and abroad
  - Post-Fukushima flood hazard reevaluations

2

Progress and Next Steps

- Phased Approach
  - Technical basis and draft guidance
  - Pilot Studies
  - Finalize Guidance
- Bulk of technical basis research should be completed in FY19
  - Precipitation
  - Local Intense precipitation (LIP) flooding
  - Riverine flooding
  - Storm surge
  - Reliability of flood protection and mitigation
  - PFHA frameworks
- Need to turn our focus towards meaningful pilot studies
  - Site-specific issues
    - e.g., coastal/estuary vs. inland/river location
  - Full hazard curves
    - Coincident and correlated flooding processes
  - Integrating flood hazard assessment information into plant risk assessment models

3

3.3.1.2 NRC Flooding Research Program Overview Joseph Kanney*, Ph.D., Meredith Carr, Ph.D., P.E., Thomas Aird, Elena Yegorova, Ph.D., and Mark Fuhrmann, Ph.D., Fire and External Hazards Analysis Branch, Division of Risk Analysis; and Jacob Philip, P.E, Division of Engineering, Structural, Geotechnical and Seismic Engineering Branch, Office of Regulatory Research, U.S. NRC (Session 1A-2; ADAMS Accession No. ML17355A083https://www.nrc.gov/docs/ML1705/ML17054C500.pdf)

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Overview of NRC Probabilistic Flood Hazard Assessment Research Program

Thomas Aird
Meredith Carr, Ph.D.
Mark Fuhrmann, Ph.D.
Joseph Kanney, Ph.D.
Jacob Philip, PE
Elena Yegorova, Ph.D.

Fire and External Hazards Analysis Branch, Division of Risk Analysis
Office of Nuclear Regulatory Research

3rd Annual PFHA Research Workshop
NRC HQ, Rockville, MD
December 4-5, 2017

1

Outline

- Objectives
- Key Challenges
- Main Themes
- Current Projects

PFHA Research Objectives

- Support development of risk-informed licensing and oversight guidance and tools for assessing flooding hazards and consequences
  - *Addresses significant gap in probabilistic basis for external hazards*
    - Seismic and wind hazard assessments currently have probabilistic basis
- Support both new reactor licensing and oversight of operating reactors
  - *Design basis flood hazard assessments for new facilities*
    - 10 CFR Part 50 - traditional construction permits and operating licenses
    - 10 CFR Part 52 - early site permits (ESPs), combined operating licenses (COLs)
  - *Operating reactor oversight program (ROP)*
    - Significance determination process (SDP) analyses for evaluating deficiencies related to flood protection at operating facilities

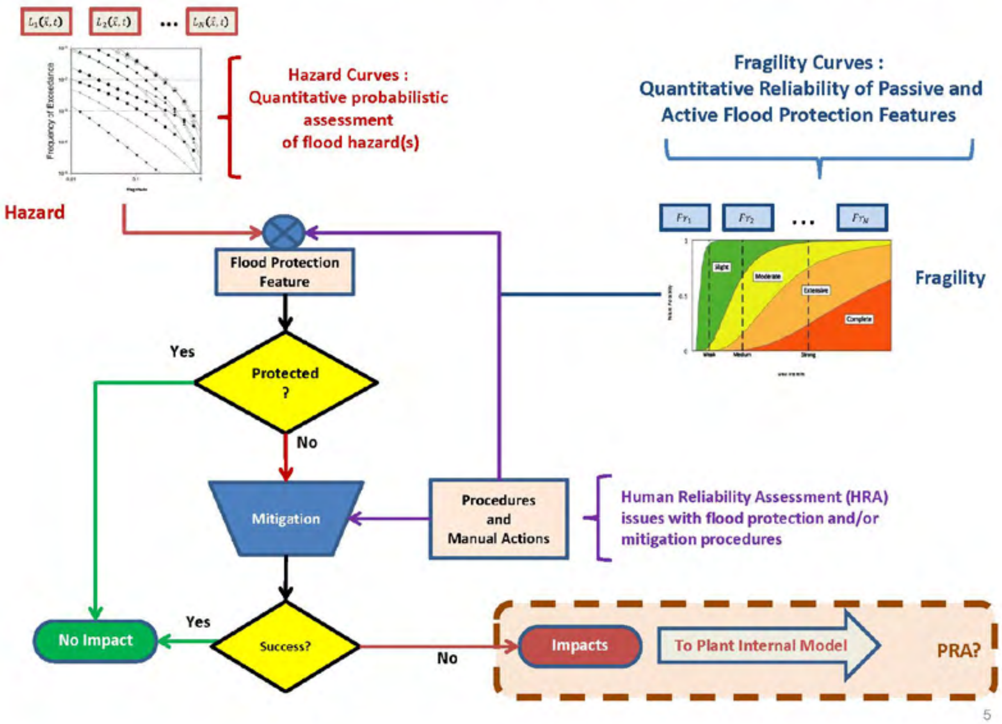
3

Implementation

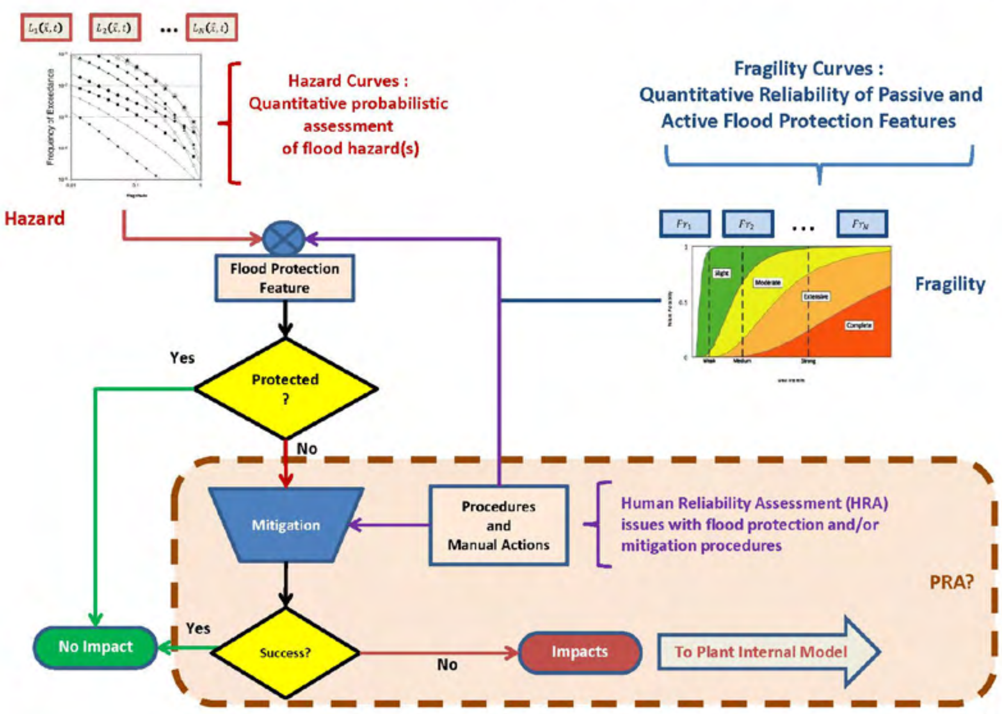
- Phased Approach
  - *Phase 1 (Technical basis, draft guidance)*
  - *Phase 2 (Pilot studies)*
  - *Phase 3 (Finalize guidance)*
- Implementation time-frame
  - *~5 years for Phase 1*
    - ***now into 4th year of implementation***
  - *~2 years for Phases 2+3*
    - ***need to begin discussion of pilot studies***
- Contract technical support
  - *Interagency Agreements*
    - *DOE Laboratories, USACE, USBR, USGS*
  - *Commercial contracts*
- External Collaborations
  - *Federal Working Groups (e.g., ACWI/SOH)*
  - *EPRI (MOU in place)*
  - *International (e.g., IRSN)*

4

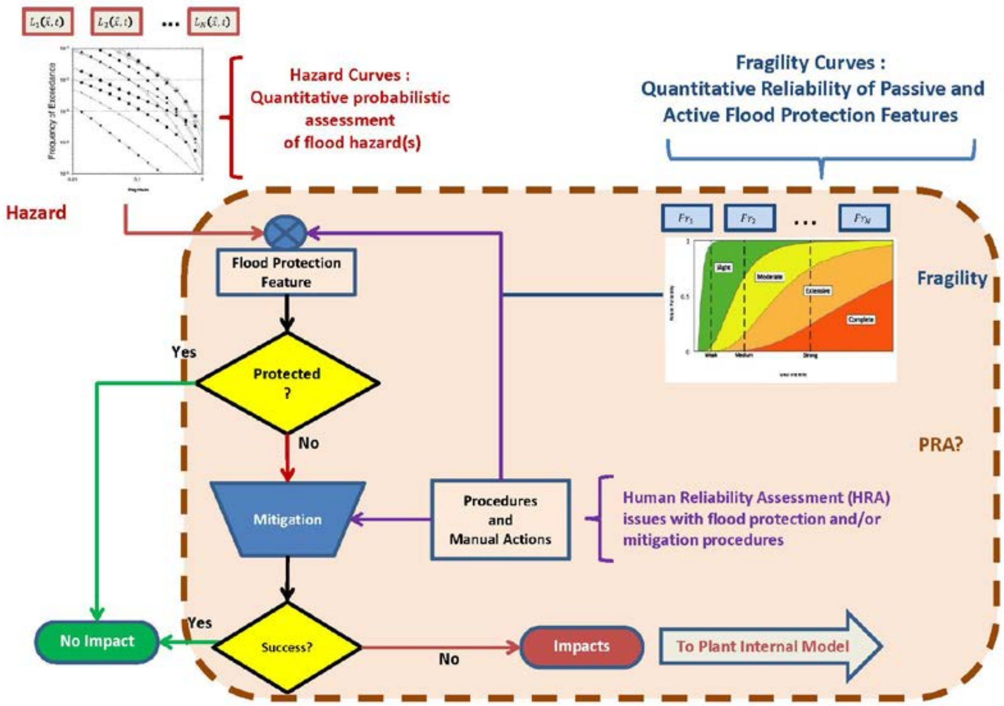
Risk-informed Assessment of Flooding Hazards and Consequences



Risk-informed Assessment of Flooding Hazards and Consequences



Risk-informed Assessment of Flooding Hazards and Consequences



7

Key Challenges

- Interested in range of annual exceedance probabilities (AEPs) from moderately rare to extreme floods
  - *Full hazard curves needed*
    - Aleatory and epistemic uncertainties
  - *AEPs in the range 1e-4 to 1e-6 desired*
- Large uncertainties
- Component fragility and human reliability information is sparse
- Flooding impacts exhibit cliff-edge effects
- Complexity
  - Coincident and correlated mechanisms
  - Associated effects

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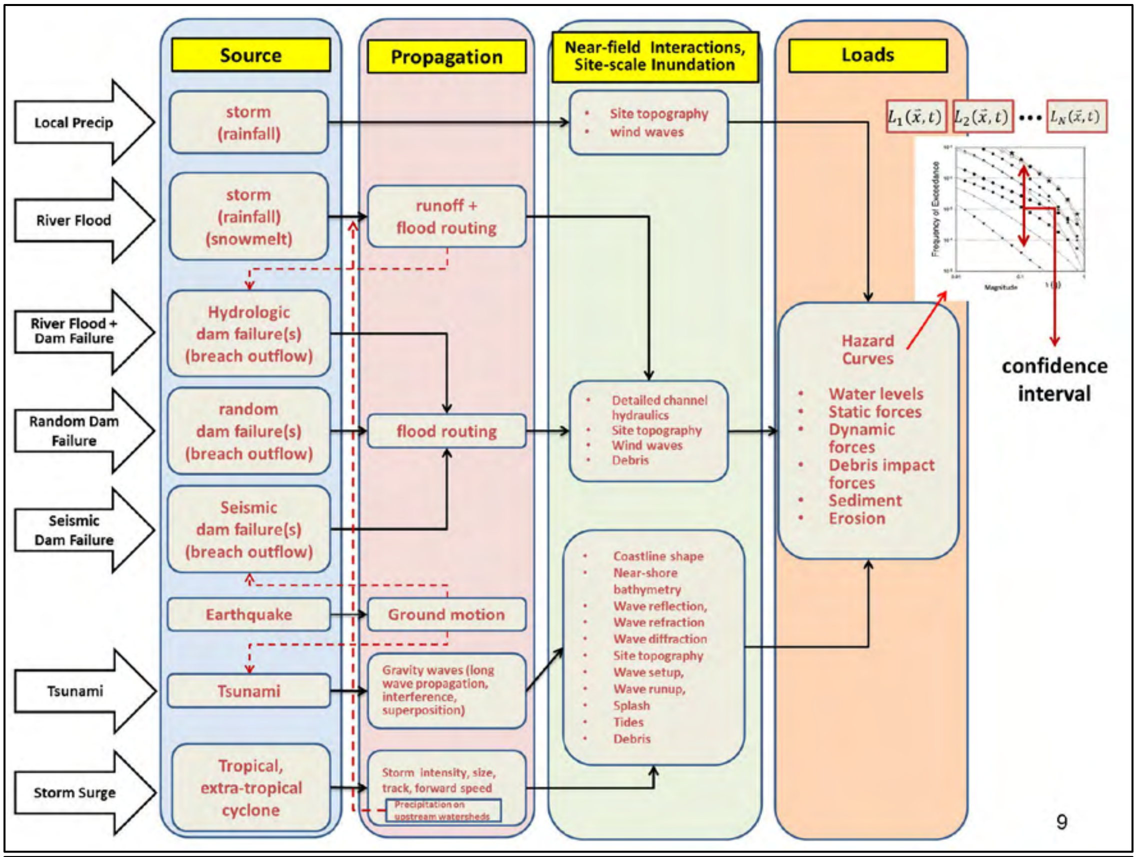

Main Research Themes

- Approaches and methods to leverage available flood hazard information
- Application of improved modeling techniques for processes and mechanisms associated with flooding
- PFHA modeling framework(s) for range of flooding scenarios and range of AEPs
- Methods to assess potential impacts of dynamic and nonstationary processes on flood hazard assessments and flood protection
- Methods to assess reliability of flood protection, mitigation, and plant response to flooding events

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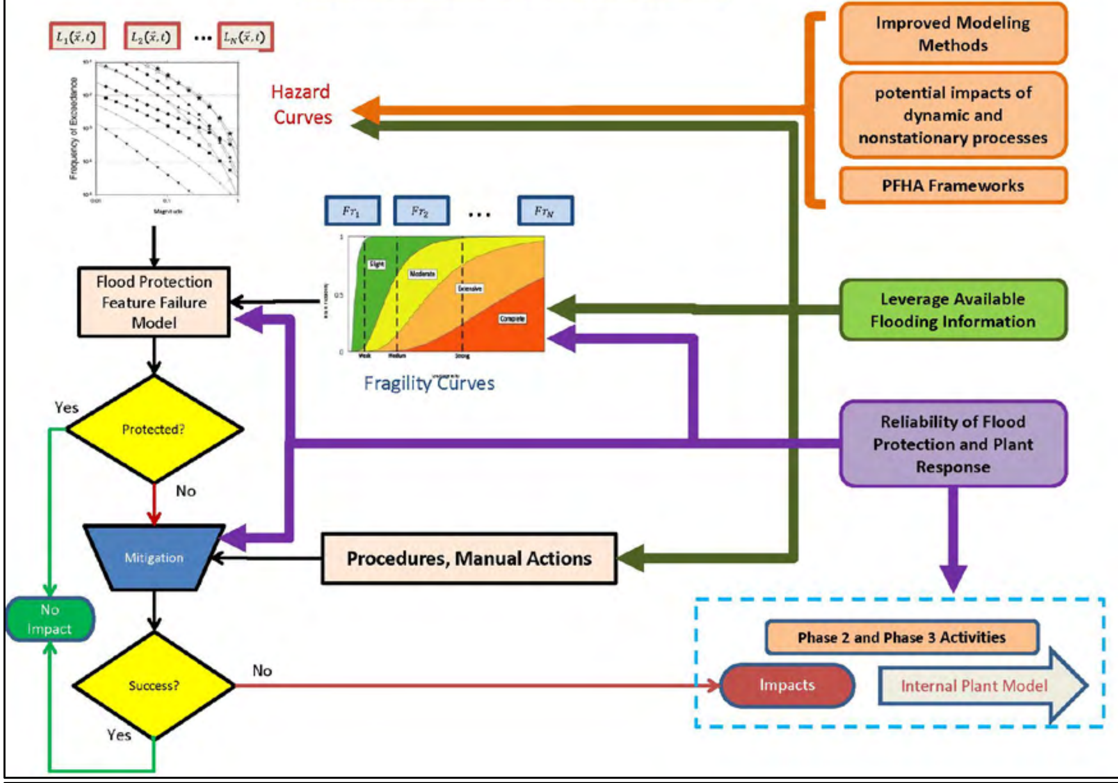
Research Themes



Current Projects

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Leverage Available Flooding Information

- **Development of Flood Hazard Information Digests for Operating NPP Sites**
  - *Contractor: Idaho National Laboratory (INL)*
  - *NRC PM: Meredith Carr*

- **Guidance on Application of State-of-Practice Flood Frequency Analysis Methods and Tools**
  - *Contractor: U.S. Geological Survey (USGS)*
  - *NRC PM: Meredith Carr*

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Leverage Available Flooding Information

- **Technical Basis for Extending Frequency Analysis Beyond Current Consensus Limits**
  - *Contractor: U.S. Bureau of Reclamation (USBR)*
  - *NRC PM: Joseph Kanney*
- **Research to Develop Guidance on Extreme Precipitation Frequency in Orographic Regions**
  - *Contractor: USBR*
  - *NRC PM: Joseph Kanney*
- **Detailed TN River Paleoflood Study**
  - *Contractor: USGS*
  - *NRC PM: Mark Fuhrmann*

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PFHA Frameworks

- **Technical Basis for Probabilistic Flood Hazard Assessment – Riverine Flooding**
  - *Contractor: Pacific Northwest National Laboratory (PNNL)*
  - *NRC PM: Joseph Kanney*
- **Probabilistic Flood Hazard Assessment Framework Development**
  - *Contractor: U.S. Army Corps of Engineers (USACE)*
  - *NRC PM: Joseph Kanney*
- **Structured Hazard Assessment Committee Process for Flooding**
  - *Contractor: PNNL*
  - *NRC PM: Joseph Kanney*

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Improved Process Modeling

- **Numerical Modeling of Local Intense Precipitation Processes**
  - *Contractor: University of California Davis/USGS*
  - *NRC PM: Elena Yegorova*
- **Quantifying Uncertainties in Probabilistic Storm Surge Models**
  - *Contractor: USACE*
  - *NRC PM: Joseph Kanney*
- **Erosion Processes in Embankment Dams**
  - *Contractor: USBR*
  - *NRC PM: Jacob Philip*

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Reliability of Flood Protection and Plant Response to Flooding Events

- **Performance of Flood Penetration Seals at NPPs**
  - *Contractor: Fire Risk Management (FRM)*
  - *NRC PM: Tom Aird*
- **Effects of Environmental Factors on Manual Actions for Flood Protection and Mitigation at NPPs**
  - *Contractor: PNNL*
  - *NRC PM: Meredith Carr*
- **Modeling Plant Response to Flooding Events**
  - *Contractor: INL*
  - *NRC PM: Joseph Kanney*

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Dynamic and Nonstationary Processes

- **Regional Climate Change Projections: Potential Impacts to Nuclear Facilities**
  - *Contractor: PNNL*
  - *NRC PM: Elena* Yegorova

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3.3.1.3 EPRI Flooding Research Program Overview John Weglian, EPRI (Session 1A-3; ADAMS Accession No. ML17355A084)

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EPRI Flooding Research Program Overview

John E. Weglian
Senior Technical Leader

3rd NRC External Flooding Research Workshop
December 4-5, 2017

Challenge with External Flooding

- External flooding hazards are assessed based on limited data
- In most places the historical record for events of interest are limited to just over 100 years
- Design basis analyses use the concept of a Probable Maximum Flood (PMF), but make no attempt to calculate the frequency of occurrence of such a flood
- Extrapolation to extremely low frequencies is required to probabilistically assess risk at nuclear power plants
  - PRA models assess risks down to a frequency of 10^{-7}/yr or lower
  - The PFHA may be required to assess the hazard frequency down to as low as 10^{-6}/yr – equivalent to an Annual Exceedance Probability (AEP) of 10^{-6}

2

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Techniques to Assess Low Frequency Flooding

- Extrapolation beyond twice the historical record is not considered to be credible
- A variety of methods are used to extend the effective historical record
  - Use of independent, but applicable measurements (e.g., rain gauges)
  - Transposition of observed storms from one location to another
  - Development of synthetic storms to simulate flooding impact with Monte Carlo analysis
  - Use of paleo (i.e., outside of the historical record) evidence to inform the data
- All of these techniques involve uncertainty, so it is important to characterize the uncertainty

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EPRI Flooding Research Topics

- Hazard Assessment
  - State of knowledge of external flooding analysis – 3002005292
  - Riverine flooding – 3002003013
  - Local intense precipitation – 3002004400
  - Storm surge – 3002008111
  - Deterministic hazard assessment – 3002008113
- Analysis Techniques
  - Use of 3-D modeling techniques for flooding – 3002010673
- Managing existing design and licensing bases for flood protection barriers
  - Flood Protection Systems Guide – 3002005423
  - External Flood Protection Design/License Basis Management Best Practices Guide – 3002010620

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State of Knowledge of External Flooding Analysis

- 3002005292 – External Flooding Hazard Analysis: State of Knowledge Assessment
- Freely available to the public
- Examines the probabilistic methods currently available to assess external flooding hazard
  - Local intense precipitation
  - Riverine flooding
  - Dam failure
  - Storm surge

Riverine Flooding

- 3002003013 – Riverine Probabilistic Flooding Hazard Analysis Pilot: Proof-of-Concept Study for a Nuclear Power Plant
- Two stochastic models used to simulate riverine flooding at a site
  - Stochastic Event Flood Model (SEFM)
  - Stochastic Runoff Routing Monte Carlo (RORB_MC)
- Includes evaluation of uncertainties, expert judgement, and sensitivities of flood-hazard estimates to the various modeling components

Local Intense Precipitation

- 3002004400 – Local Precipitation-Frequency Studies: Development of 1-Hour/1-Square Mile Precipitation-Frequency Relationships for Two Example Nuclear Power Plant Sites
- Freely available to the public
- Maximizes available data by finding independent and applicable data sources and combining them

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Storm Surge

- 3002008111 – Probabilistic Flooding Hazard Assessment for Storm Surge with an Example Based on Historical Water Levels
- Provides process for performing a probabilistic storm surge hazard assessment
- Provides an example using historical water levels rather than simulating the storm parameters

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Deterministic Hazard Assessment

- 3002008113 – Evaluation of Deterministic Approaches to Characterizing Flood Hazards
- Freely available to the public
- Uses the Hierarchical Hazard Assessment (HHA) process in NUREG/CR-7046
- Examines the assumptions, inputs, and methods used for assessing external flooding hazards
  - Provides suggestions where changing of assumptions, inputs, and methods might provide a more realistic, yet still bounding assessment

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Use of 3-D Modeling Techniques for Flooding

- 3002010673 - Investigation into the Use of Three-Dimensional Modeling Techniques to Assess Internal Flooding Scenarios
- Freely available to the public
- EPRI examined the use of Smoothed Particle Hydrodynamics (SPH) for modeling of internal flooding scenarios
  - Conclusions found that in most cases, the use of 1-D techniques is sufficient
  - SPH can be beneficial to capture spray or splash effects or when the PRA is sensitive to the timing of component failures
- EPRI did not investigate the use of SPH for external flooding, but the technique may be useful for those scenarios

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EPRI's NMAC Flood Protection Research

- 3002005423 – Flood Protection Systems Guide
  - Characterizes the flood protection systems in place
- 3002010620 - External Flood Protection Design/License Basis Management Best Practices Guide
  - Collects the administrative best practices across the industry on how to manage the design and licensing bases

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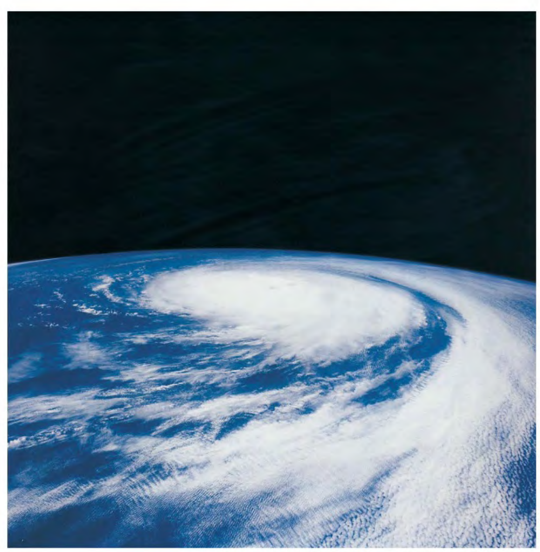
Near-Term EPRI External Flooding Research

- Collection of paleoflood evidence - 3002010667
  - Report at end of 2017
- Guidance on conducting PRA external flooding walkdowns
  - Publication and training in 2018



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Potential Future External Flooding Research

- Hazard assessment
  - Use of paleoflood data in risk-informed approaches
  - Estimation of frequency of hurricane-driven storm surge
  - Seiche and tsunami frequency estimation
  - Dam failure
- Analysis technique
  - External flooding PRA model development guidance
  - Correlated hazards modeling (e.g., storm surge and wind)
- Flood barrier fragility

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Together…Shaping the Future of Electricity

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EPRI ELECTRIC POWER RESEARCH INSTITUTE

3.3.1.3.1 Question and Answers

Question:

Are the EPRI reports discussed in this presentation free to the general public?

Response:

So, the report's that specifically say they're freely available to the public, anybody can get to them if you go to EPRI.com and you type in the number. In fact, this presentation has hyperlinks so if you follow that hyperlink for the public ones, it should take you to the public side of EPRI.com, where you can download that report for free. For those that did not specifically say "freely available" to the public, they are not free to the public. Members have access to those information and members of the public who choose to pay for them could also buy them in that way. EPRI prefers that you, even for the free to the public reports, that you go to the site and download your own copy rather than sharing it -just so we know how useful our materials are. We track that information so that we would know if everybody in this room downloaded one report, that report must be pretty important.

Question:

You commented on your 3D modeling the smooth vertical hydrodynamic model and it was for internal flooding only –not external.

Response:

But the research that we did was using internal flooding. We simulated flooding in a particular room that propagated through a stairway into another room and the point of that research was to see if there are new risk insights using this approach compared to what the industry is currently using. That's why we used an internal flooding scenario because there are internal flooding models that are out there that we could compare against and so that's why we looked at the internal flooding for that.

Question:

With regard to your correlated hazard models…have you thought about it at the Blayais site, the argument is that when the water table obviously exceeds the surface and it could be as you just described with the water cascading down the stair, coming through pipes, whatever…how have you thought about combing the external hazard with the internal?

Response:

So, that's a good point. If the water sticks around long enough it can get into the groundwater and you may have…the utility that I came from, they had a pipe to measure groundwater and it's just an open pipe and if the groundwater got high enough, you would expect water to be coming out of that. So, to do an external flooding hazard assessment, you need to take that into account and that's a function of how long/high the water is around the site and how long it stays there. Local intense precipitation–probably not an impact. Riverine flooding, if it stays there for a couple months, almost certainly is and that would part of your hazard assessment. We tend to think, well maybe some of the practitioners are a little more nuanced but people that are not flooding experts, and before this, I was certainly in that category, think of flooding as just a water level. But there's a lot that goes into it. NRC had in their slides a bunch of different things and time of water staying there is part of it which can feed into it. So, to do an overall hazard assessment, you have to look at these other effects that the flooding can bring with it and that's certainly part of it. And if you had that effect then you would have to start looking at the retention capability of some pumps that can remove that and determine what's your ingress rate and your removal rate and does that cause you a problem or not.

Question:

You mentioned bounding assessments specifically to say a basin average three-day precipitation what scientific evidence do you have for bounds? In that research? Given the modeling that has been done in the community the past five years with WRF and uncertainties. We're searching for that elusive bound…

Response:

Yeah, I did not mean to imply that EPRI has come up with one. I was saying the techniques used try to do that kind of bounding assessment on the deterministic side. I should not imply that EPRI has looked at that at all because none of the research that I talked about actually focused on estimating a bound to how much water can be provided or it can be like held in the atmosphere or things like that.

Question:

Yeah, I just bring this up to point out two things that are currently at hot topics in the literature. One is: we see no evidence of bounds from observations and two: in a warming environment there are open questions on to what a bound might be on precipitation.

Response:

Yeah that's a good point. I know I've seen when you estimate that the hazard curve there's usually two different forms that the hazard curve takes. One looks at the discharge rate as a function of frequency, and using the statistical approaches that we use, it usually does not look asymptotic. Right it looks like it just gets a bigger and bigger, faster and faster as you go lower in frequency. But then, when you convert that to what you have at a site, now this takes into account: are you in a narrow canyon or are you in a plane that they can spread out widely. So even if the discharge, say for riverine flooding, is continuing to increase without a bound, the flood level at your site may be more asymptotic. It depends on the topography near your site but typically the flood hazard curves at least for riverine flooding –I do see them -not the discharge itself- the amount of water coming is not typically shown as being asymptotic. So, it shows that there may not be a bound. It's just lower and lower frequency to get these higher and higher levels.

Question:

What is the cost-benefit comparison between using the SEFM model versus the RORB_MC model?

Response:

I was not involved in that study during my time at EPRI, so I was about to answer your question until you said cost-benefit. I don't know the cost-benefit analysis. I do know from looking at the two models, they seem to be in relative agreement. They were certainly within the uncertainty bounds of each other. The means diverged a little bit at the lower frequencies. I would have to ask the people that actually focus on that research in terms of “was one more time-intensive to perform than the other?” I'm just not familiar with those details. The RORB model did take less resources than the SEFM model.

3.3.2 Day 1: Session 1B - Climate and Precipitation

Session Chair: Elena Yegorova, NRC/RES/DRA/FXHAB

Development of guidance for application of improved mechanistic and probabilistic modeling techniques for key flood generating processes and flooding scenarios.

Assessment of the potential impacts of dynamic and nonstationary processes on flood hazard assessments and flood protection at nuclear facilities.

3.3.2.1 Regional Climate Change Projections: Potential Impacts to Nuclear Facilities L. Ruby Leung^, Ph.D. and Rajiv Prasad*, Ph.D., Pacific Northwest National Laboratory (Session 1B-1; ADAMS Accession No. ML17355A085)

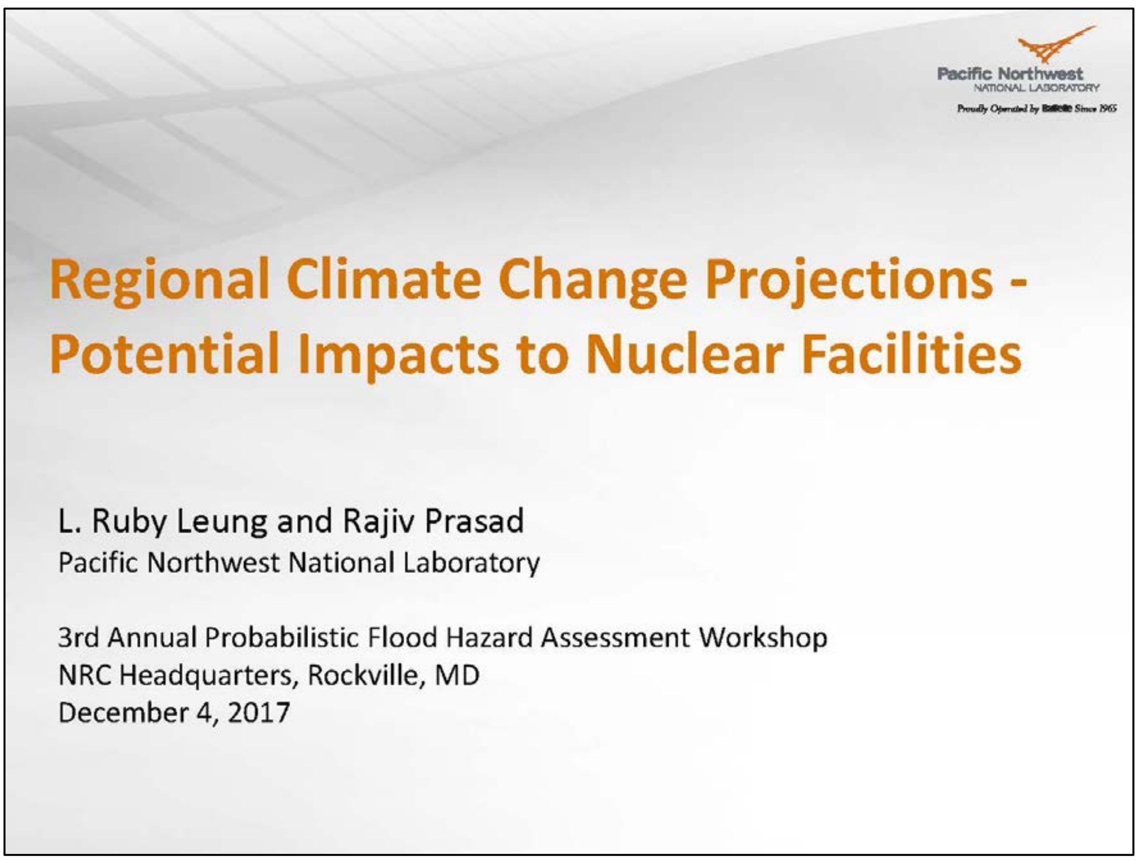
3.3.2.1.1 Abstract

This project is part of the NRC’s Probabilistic Flood Hazard Assessment (PFHA) research plan in support of developing a risk-informed licensing framework for flood hazards and design standards at proposed new facilities and significance determination tools for evaluating potential deficiencies related to flood protection at operating facilities. The PFHA plan aims to build upon recent advances in deterministic, probabilistic, and statistical modeling of extreme precipitation events to develop regulatory tools and guidance for NRC staff regarding PFHA for nuclear facilities. An improved understanding of large-scale climate pattern changes such as changes in the occurrence of extreme precipitation, flood/drought, storm surge, and severe weather events can help inform the probabilistic characterization of extreme events for NRC’s permitting, licensing, and oversight reviews.

This project provides a literature review, focusing on recent studies that improve understanding of the mechanisms of how the climate parameters relevant to the NRC may change in a warmer climate, including discussions of the robust and uncertain aspects of the changes and future directions for reducing uncertainty in projecting those changes. During the first year, the project reviewed various aspects of climatic changes across the U.S., while the second year focused on more detailed changes in the southeastern U.S. The current focus is on the Midwest region consisting of 8 states (Minnesota, Wisconsin, Michigan, Iowa, Missouri, Illinois, Indiana, and Ohio) in the conterminous U.S. Except for Indiana, all states have currently operating nuclear power plants. The literature review includes an overview of the climate of Midwest U.S., including temperature and precipitation extremes, floods and droughts, severe storms and strong winds including mesoscale convective systems, tornadoes, hail storms, and lake effect snow storms, Great Lakes water level, and flooding due to various mechanisms including heavy precipitation from convective storms in the summer and extratropical cyclones in the winter and snowmelt in spring. For each climate variable or phenomenon, the report discusses the climatological features over the Midwest region, the historical changes observed in the past, and the projected changes in the future, drawing on major reports from the National Climate Assessment and peer-reviewed

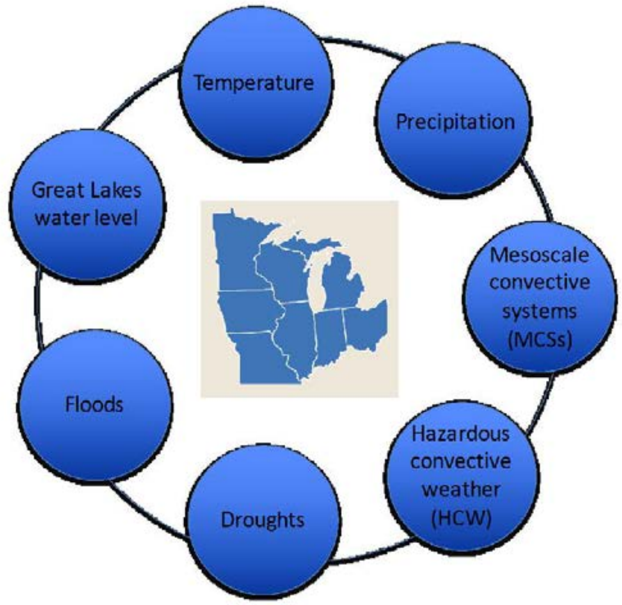
papers in the literature. Overall, mean and annual 5-day maximum temperatures are projected to increase in the future. With increasing moisture accompanying the warmer temperatures, precipitation is projected to increase in the cool season, but the changes in warm season precipitation are not statistically significant. Despite inconsistency in mean precipitation changes across the seasons, extreme precipitation (99th percentile) is projected to increase by more than 10% and 30% by the end of the 21st century under the RCP4.5 and RCP8.5 emissions scenarios, respectively. A regional climate modeling study at 4 km resolution projected more than tripling in the frequency of intense mesoscale convective systems in the summer. This is consistent with observational evidence of an increase in mean and extreme precipitation associated with mesoscale convective systems over the Midwest in the past 35 years. Lake effect snow storms are projected to increase as reduction of the surface area of lake ice with warming increases evaporation from the surface, but larger warming farther into the future may shift snowfall events into rain events. The Great Lake level has exhibited large variability historically. Models projected small decreases in the lake level but the range of uncertainty across model projections is large. Observational records over the Midwest show strong evidence of increasing flood frequency but limited evidence of increasing flood peaks. With the increase in extreme precipitation and storm events projected for the future, flooding is projected to increase notably in the future. Projected increase in average number of days without precipitation could lead to agricultural drought and increased cooling water temperatures.

3.3.2.1.2 Presentation



The Midwest region

- **Midwest Region in NCA3 and NCA4**: Illinois, Indiana, Iowa, Michigan, Minnesota, Missouri, Ohio, Wisconsin
- All states in the Midwest Region except for Indiana, have operating nuclear power plants

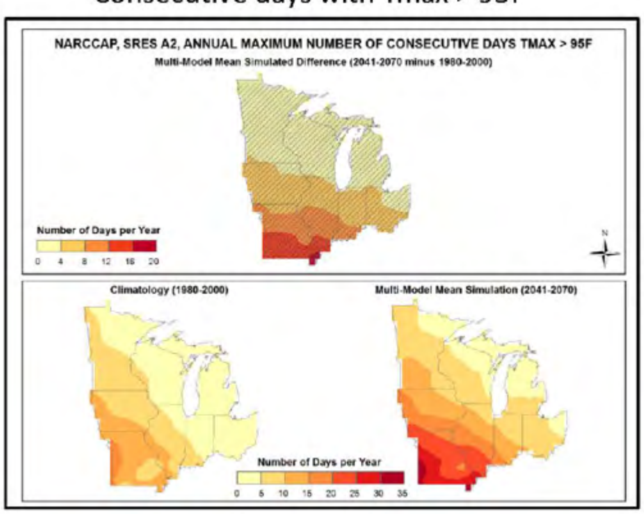


NCA4 regions

Changes in hot days

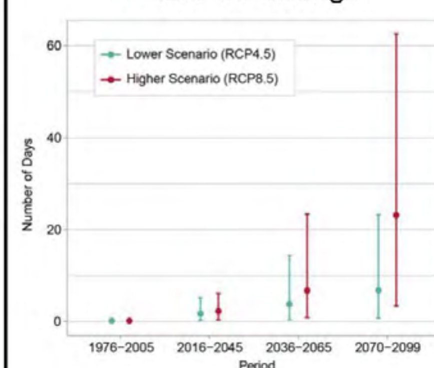
- Increase in heat extremes can pose challenges to infrastructure (e.g., material stress) and rising stream temperature may affect power plant operations

Consecutive days with Tmax > 95F



NCA3 report

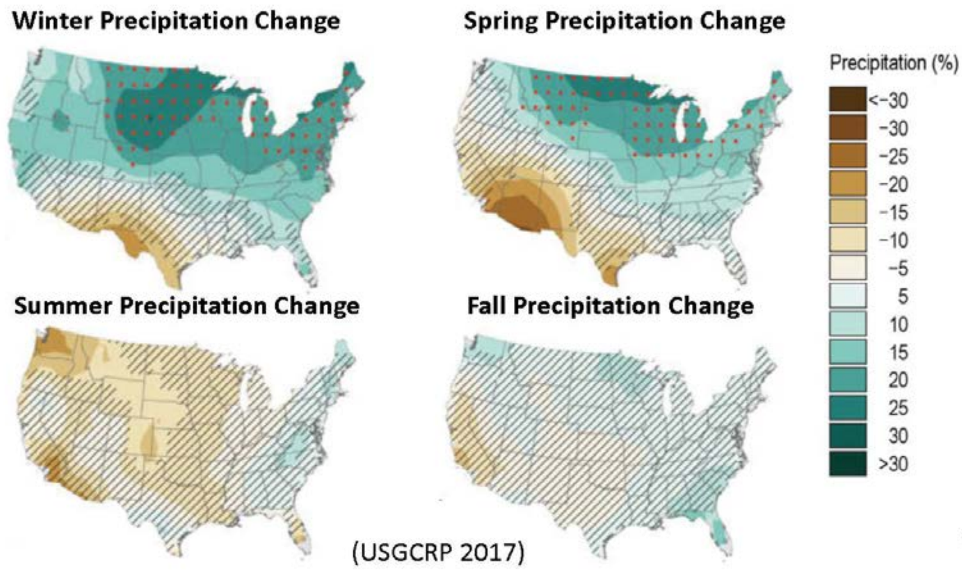
Projected number of days > 100F for Chicago



NCA4 report

Seasonal precipitation changes

- Annual precipitation in the Midwest has increased by 5% to 15%from 1901–1960 compared to 1986–2015
- Increase in cold season precipitation due to poleward shift of storm tracks



(USGCRP 2017)

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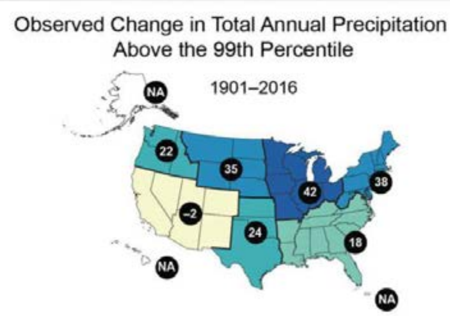
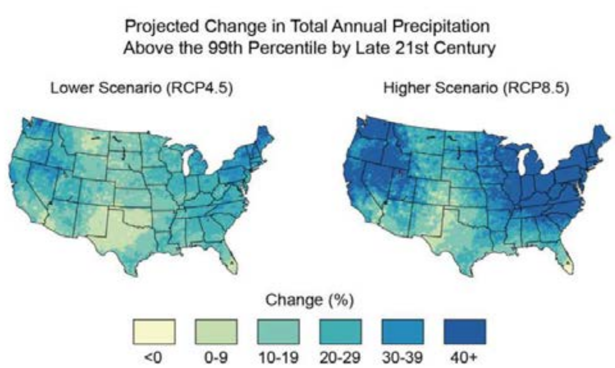
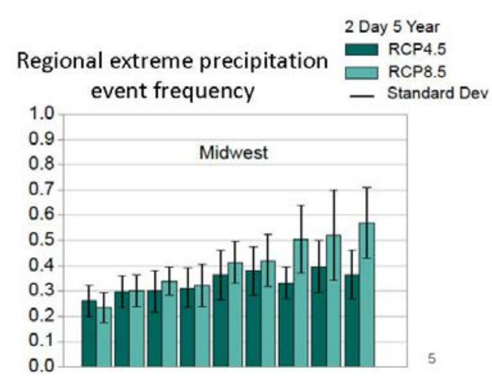
Changes in extreme precipitation

- Observed changes are largest over the Midwest
- Projected changes are largest over the Midwest and western U.S.





(USGCRP 2017)



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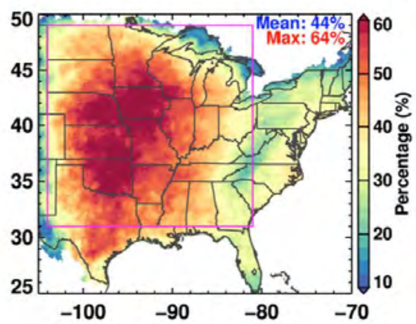
Contribution of MCS to mean and extreme precipitation

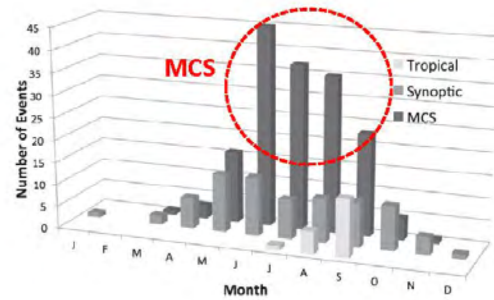
- Mesoscale convective systems (MCSs) play a critical role in producing heavy rainfall in the tropics and mid-latitudes during warm seasons
- In Midwest, MCSs contribute 30%-60% of the total warm-season rainfall
- Most of 100-yr, 24-h extreme rainfall events east of the Rocky Mountains were caused by MCSs in the warm season (Stevenson & Schumacher 2014)

15-year MCS precipitation climatology



(Feng et al. (2016) Nature Commun.)

Extreme Event Types

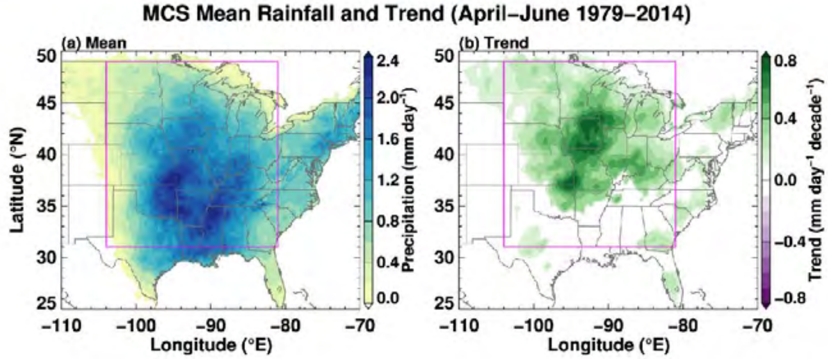


(Stevenson & Schumacher 2014 MWR)

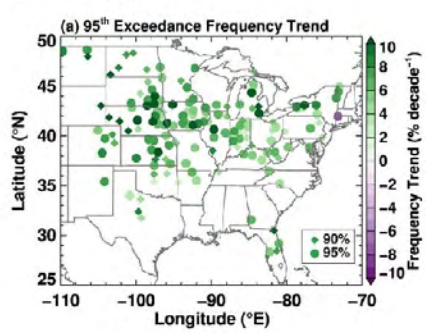
6

MCS rainfall increased in the past

MCS Mean Rainfall and Trend (April–June 1979–2014)



- Some regions in Midwest experienced 0.4-0.8 mm day^{-1} (20-40%) increase in MCS precipitation
- 95th percentile MCS hourly rain-rate increased consistent with mean MCS precipitation increase



(Feng et al. 2016 Nature Commun.)

Changes in large-scale environment

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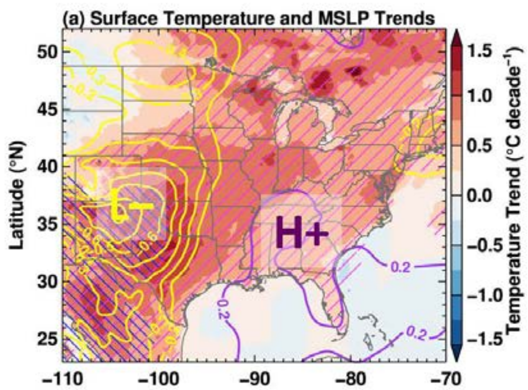
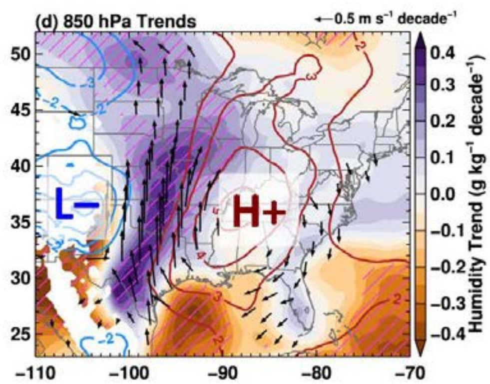
Surface trend | **850 hPa trend**





- Surface warming over land and lack of warming in surrounding oceans increase pressure gradient across central US
- Low-level moistening associated with enhanced GPLLJ moisture transport facilitates more intense MCS precipitation

(Feng et al. 2016 Nature Commun.)

8

Changes in hourly extreme precipitation from convection permitting simulations

Pacific Northwest NATIONAL LABORATORY
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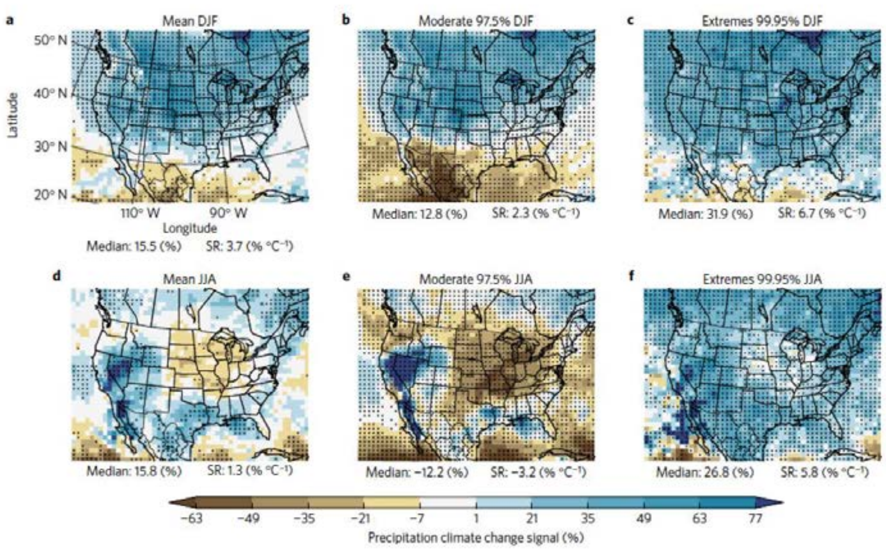
Precipitation change (%) for 2071-2100 relative to 1976-2005: increase in 99.95% hourly precipitation everywhere

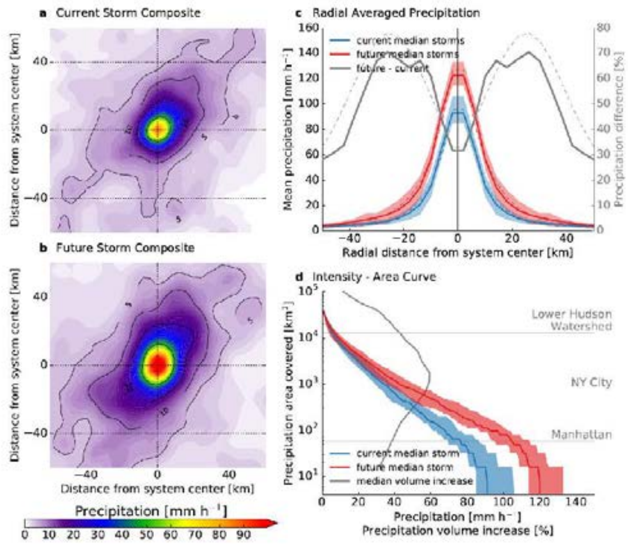


(Prein et al. 2016 Nature Climate Change)

9

Changes in MCS precipitation

- Intense summertime MCS frequency will more than triple in North America
- MCSs that move slower than 20 kmh^{-1} reduce their speed by up to 20% in the Midwest, Mid-Atlantic, and Canada



(Prein et al. 2017 Nature Climate Change)

Simulating changes in HCW

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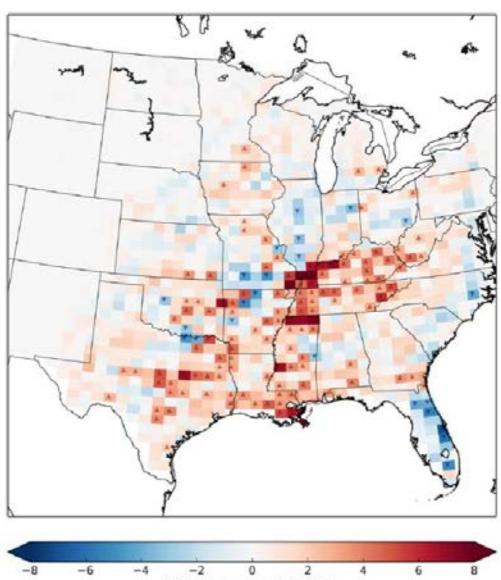
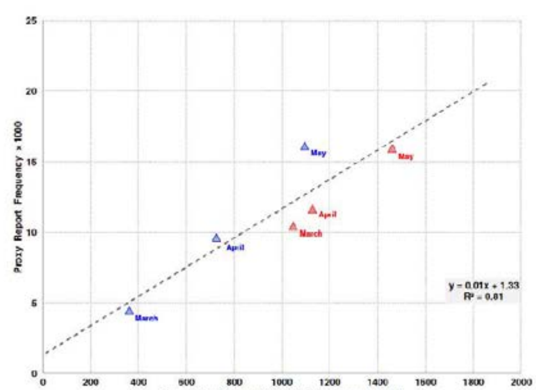
Average difference between 2080–2090 and 1980–1990 modeled severe weather reports



Environmental conditions explain over 80% of the variance associated with modeled reports during March–May

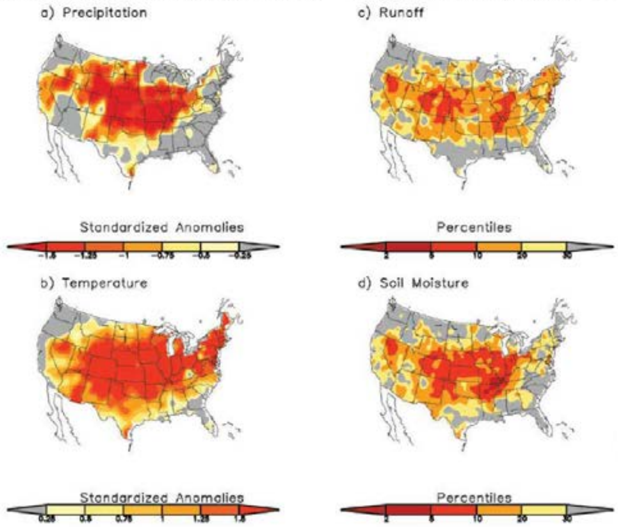


(Gensini and Mote 2015 Climatic Change)

Midwest droughts - historical

- Meteorological (precipitation deficit), Agricultural (soil moisture deficit), and Hydrological (runoff/streamflow deficit)
- 2012 Great Plains/Midwest drought, most severe observed meteorological drought - caused by large-scale meteorology reducing rain during summer (May-August, 2012)

Standardized anomalies over May – Aug 2012 relative to 1979-2011



(Hoerling et al., 2014 BAMS)

13

Midwest droughts - projected

- Increases in temperatures in the future are expected to result in increases in evapotranspiration exceeding increases in precipitation, leading to increased soil moisture deficits and agricultural droughts

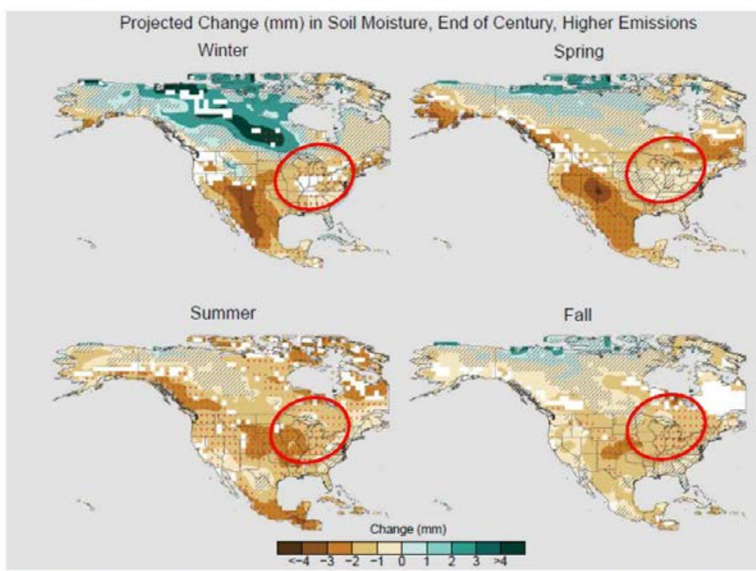


Figure 8.1: Projected end of the 21st century weighted CMIP5 multimodel average percent changes in near surface seasonal soil moisture (mrsos) under the higher scenario (RCP8.5). Stippling indicates that changes are assessed to be large compared to natural variations. Hashing indicates that changes are assessed to be small compared to natural variations. Blank regions (if any) are where projections are assessed to be inconclusive (Appendix B). (Figure source: NOAA NCEI and CICS-NC).

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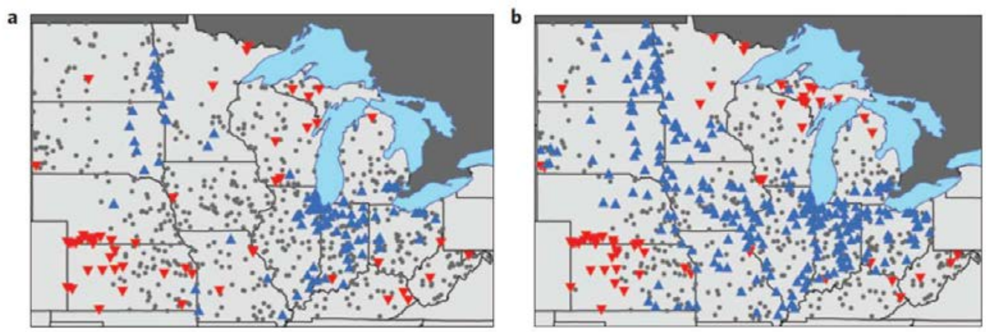
(USGCRP 2017)

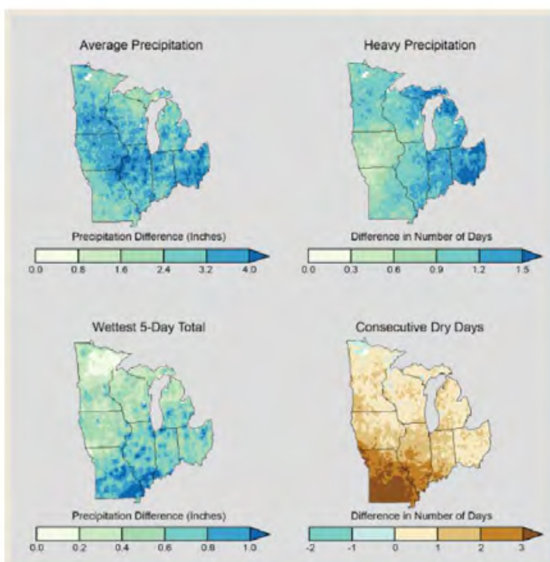
Midwest floods - historical

- 2008 floods (USGS Professional Paper 1775)
  - Above-average snowpack, record precipitation, saturated soils, remnants of two hurricanes
  - Separate flooding events in January through July, and September 2008
  - Affected all states in the Midwest Region except Ohio
- 2011 floods (USGS Professional Paper 1798-B)
  - Large snowpack, near-record spring rainfall, large releases from dams
  - Flooding from February through September 2011
- Mallakpour and Villarini, 2015, 2016



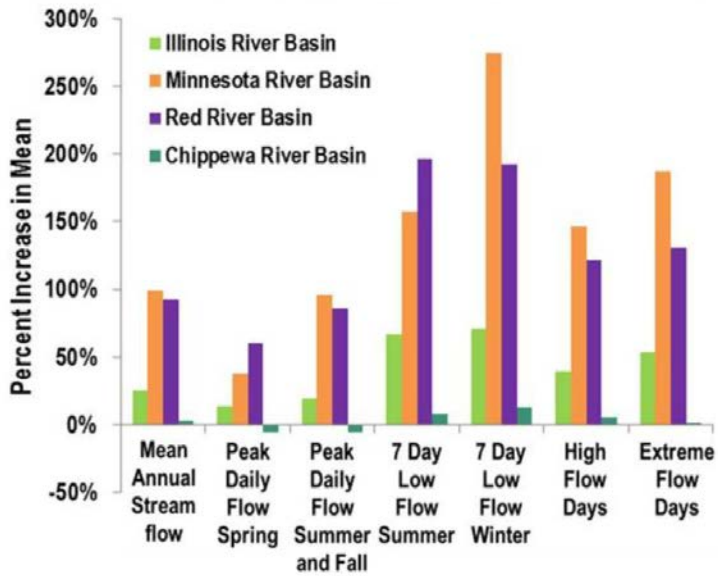
Midwest floods - projected

- Projected future floods
  - NCA3: Increases in rainfall and flooding are expected to continue in the future
    - Total amount of precipitation to increase
    - Number of days with top 2% of rainfalls to increase
    - Wettest 5 -day total precipitation to increase
    - Consecutive dry days to increase (related to droughts)
    - Warm-season precipitation to increase
  - NCA4:
    - Frequency and intensity of heavy precipitation events to increase (high confidence); based on physical reasoning local flooding in some catchments or regions would increase (medium confidence)



Midwest streamflow - historical

- EPA Climate Change Indicators, 2016
  - Mean annual streamflow
  - 3-day high streamflow
  - 7-day low streamflow
  - Timing of spring runoff
- Kelly et al., 2016; Gupta et al., 2015



17

Midwest streamflow - projected

- Projected future streamflow
  - Demaria et al., 2016
    Chien et al., 2013

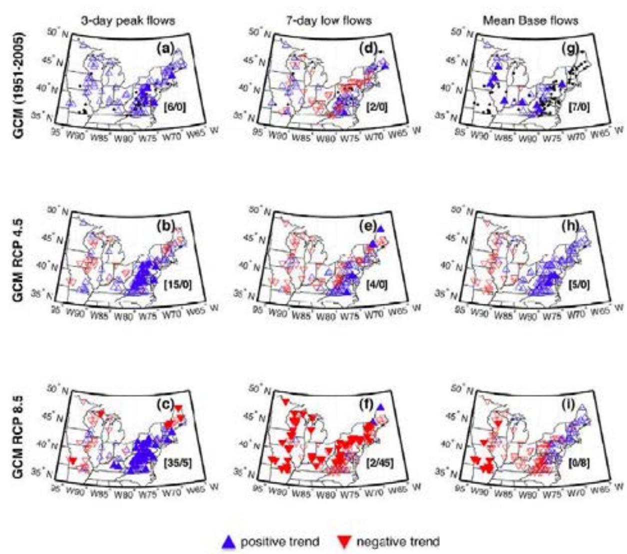


Fig. 5. Trends in GCM-driven simulations of 3-day peak flows (left column), 7-day low flows (middle column), and annual pre-whitened mean base flows (right column), during the historical (1951–2005) and future (2028–2082) periods. The black dot indicates the location of basins with statistically significant (α 0.05) point changes in the mean using the Pettitt test in Fig. 4. The numbers in the lower right corner indicate the percentage of basins with statistically significant trends.

Great Lakes water levels - historical

Pacific Northwest NATIONAL LABORATORY
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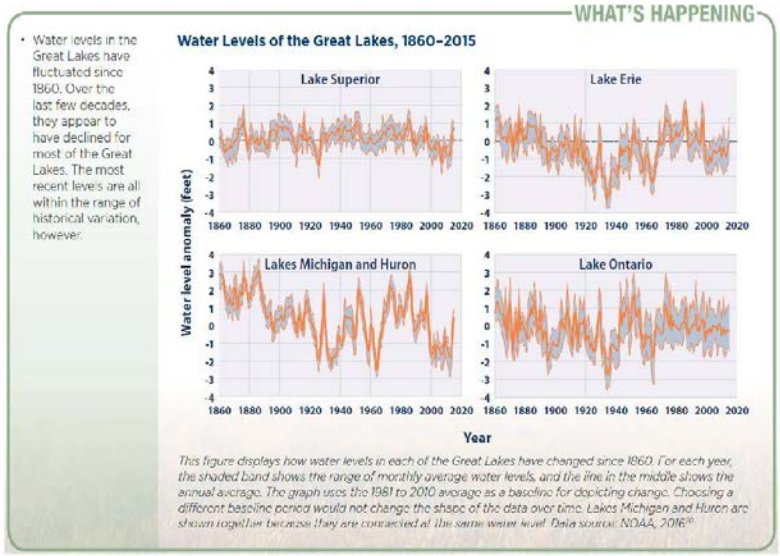
- Historical water levels
  - EPA Climate Change Indicators 2016; International Upper Great Lakes Study, 2012



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Great Lakes water levels - projected

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

- Projected future water levels
  - International Upper Great Lakes Study, 2012
  - NCA3: Angel and Kunkel, 2010; MacKay and Seglenieks, 2012

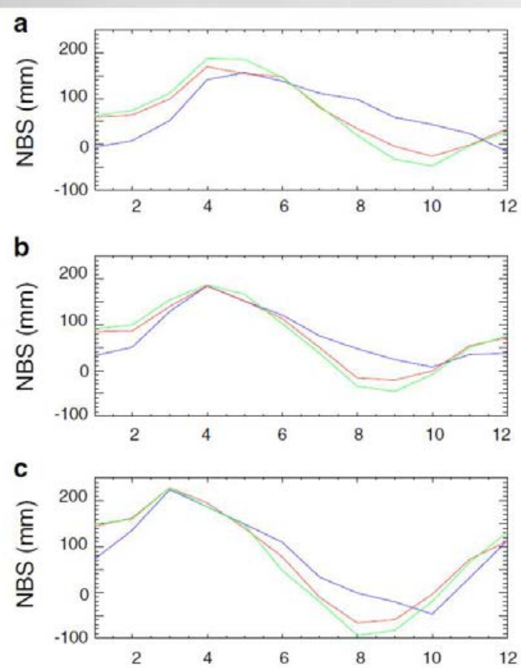
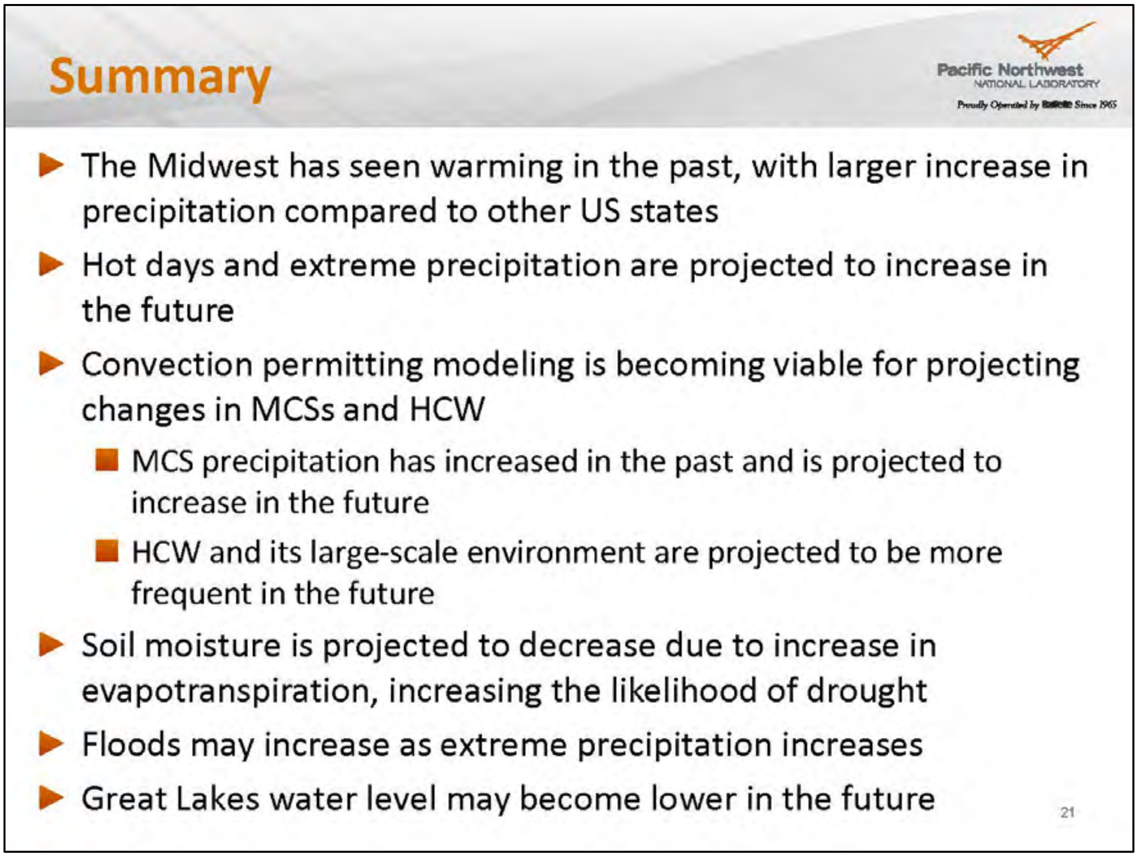


Fig. 3 NBS mean seasonal cycle for: **a** Lake Superior; **b** Lake Michigan – Huron; **c** Lake Erie. blue-observed (EC residual method); red-GLRCM 1962–1990; green-GLRCM 2021–2050. Units are mm over lake surface area

20



3.3.2.1.3 Questions and Answers

Question:

Have you had the opportunity to read Marty McCann 's study on the 2002 drought? It was interesting. So, the question is on persistence and what the variable of interest is? So, for those who haven't looked in the Midwest drought in 2012, they're claiming a record. The interesting story hydrologically and for maybe some of the facilities may be the persistence of droughts where the thirties duration was longer. So, the question is, have you had the opportunity to look at durational effects rather than single magnitudes? And whether there be a precipitation or on either end of the tales?

Response:

I haven't looked at that yet but there are certain papers which say that the durations of the droughts are going to increase. Those are very relevant in terms of if you are operating a plan and you have low water supplies combined with if you are getting the water supply from the Great Lakes. Obviously with the lower levels going down, you have a concern not in terms of flooding but in terms of operating the plant itself. Yes.

Question:

David Bowles, emeritus Utah State. I'm curious in the percentiles that you showed in your various results, do you incorporate aleatory variability in that or is there epistemic uncertainty associated with the various types of modeling that go into those estimates as well?

Response:

So, I assume that you're talking about the precipitation. So, those are based on a collection of global climate model projections and so essentially the kind of uncertainty that has been incorporated include several things. One is that they look at both the so-called high-end scenario versus the low-end scenarios so that would if you're kind of like the range. And then because it is a multi-model that also gives you some uncertainty related to how processes are being represented in different climate models. As well as looking at a longer range, looking at the internal variability as well. So, it's really essentially three sources of uncertainty can be considered using that type of approach but there are obviously other types of sources as well that that may not have been considered.

Question:

Bill Kappel from Applied Weather Associates. Great presentation just a quick two-part question one on the modeling aspect and one on the meteorological aspect of the presentation. Early on in the slides you had a slide which showed the hot days in Chicago which had an observed normal period from 1986 to 2005 then two periods after that what showed significant warming starting in 2016 and the question I have on that is first of all the observed data at least for Chicago doesn't show the same trend. In fact, the hottest days in Chicago happened in the 1940s, 50s, and 80s, and so the first question is if the observed data isn't fitting the trend that's showing in that graphic and specifically between 2005 and 2016 there has not been any increase, how does that marry up of the modeling environment if it's not correct in the beginning? Why would we think would be good going forward? And this is not specific for uses of any model, so that's the first question of how we deal with that uncertainty in the models it's not matching observations. The second part of the question is the highest temperatures recorded in Chicago just being specific to Chicago have been in the 1930s, 50s, 1988, and 2012. All those periods were significant drought periods, and that makes sense. Yet on your model projections, you showed that precipitation was going to be increasing significantly in Chicago. So, I'm just trying to figure out that incongruity there where if it's going to have higher precipitation you would expect it to actually have not as extreme temperatures. Anyway, so just those two kinds of questions on the modeling environment if you can answer those please.

Response:

Okay so I can comment on the on the first question. I think you're right that what basically these results showing here from the NCA full report is only based on model projections so there's no particular process in terms of reconciling the model projection into the future with what the models simulate in the past. That could be inconsistent with regard to that and also for the point that these are based on results from mostly four models that have pretty close resolution. So, if you look at a specific city like Chicago, there might be local effects in terms of urbanization, as well as lake effects, and other things that are not being captured by these global climate model projections. So obviously, a lot more needs to be done in terms of reconciling the observed record, especially for a particular location with climate model projections that are much broader scale. The second part of the question about the increasing precipitation but at the same time why do we have that sort of this drought?

Question:

Sorry, and by the way, I understand these are all models. I'm just trying to clear this up. In the temperature records for Chicago, specifically, all the hottest days have been during significant drought periods, so if that's the case going forward, what you would expect it to be then if it's going to have more days of wet weather or higher precipitation, you would expect the temperatures to not be as hot consecutively as in the past when it wasn't drought.

Response:

One thing the studies are mentioning is that there is not really a local scale assessment that is available for you to look at and try to make these determinations. But at the same time, generally speaking, they're saying if the temperatures are increasing in the future then you might be having elevated evapotranspiration and if that is happening, basically taking the conditions that are predicted by the larger scale modeling and trying to put in context of the physical nature in which the hydrology actually works. So, if you look at that, then they're just making a general statement that this is what we expect to happen. Now with the NCA4 Volume 2 coming out which is going to describe a lot of the regional studies, we might be able to see some more evidence of this thing.

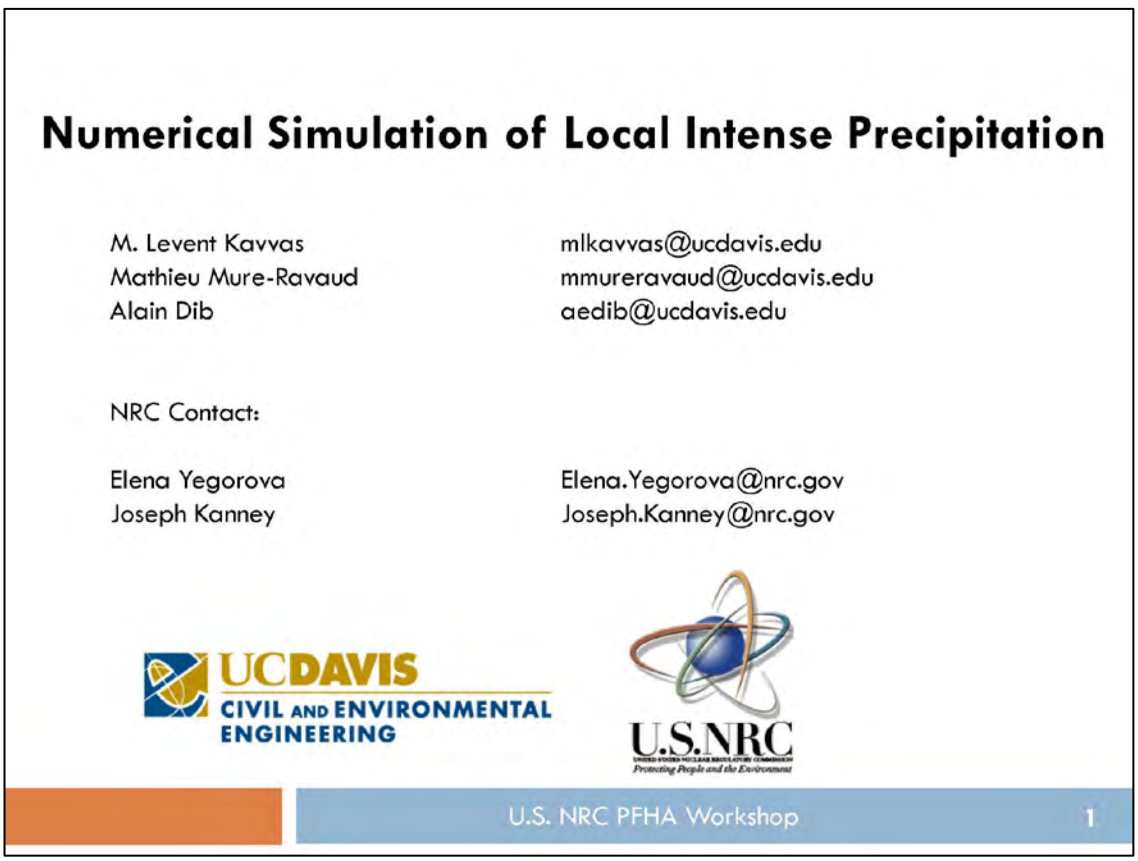
3.3.2.2 Numerical Modeling of Local Intense Precipitation Processes M. Lev Kavvas , Ph.D. Mathieu Mure-Ravaud**, and Alain Dib*, Hydrologic Research Laboratory, Department of Civil and Environmental. Engineering, University of California, Davis (Session 1B-2; ADAMS Accession No. ML17355A086)

3.3.2.2.1 Abstract

As population and infrastructure continue to increase, our society has become more vulnerable to extreme events. Flood is an example of a hydro-meteorological disaster that has a strong societal impact. Tropical Cyclones (TCs) and Mesoscale Convective Systems (MCSs) are recognized for their ability to generate intense precipitation that may in turn create disastrous floods. TCs are intense atmospheric vortices that form over the warm tropical oceans, while MCSs are organized collections of several cumulonimbus clouds which interact at the meso-scale (regional-scale) to form an extensive and nearly contiguous region of precipitation. In this study, the suitability of a regional atmospheric model (RAM) to simulate local intense precipitation processes within intense MCSs was first assessed. More specifically, the Weather Research and Forecasting (WRF) model was used at 5-km resolution in order to reconstruct the intense precipitation fields associated with several historical MCSs which affected the United States. The storm systems were selected within the time period from 2002 to the present, based on the NCEP Stage-IV precipitation dataset, which is a mosaic of regional multi-sensor analysis generated by the National Weather Service River Forecast Centers (RFCs) since 2002. These storms correspond to the most severe storms, in terms of the generation of an intense precipitation field containing pockets of extreme rainfall. The model's simulation nested domains were set up over a region in the Midwest so that the innermost domain covered the severe precipitation areas caused by these storm systems. The WRF model was configured to obtain the best results for the simulation of each of the selected severe MCSs storm events with respect to the simulated and observed precipitation fields. The simulations results were compared with the observations from the Stage IV precipitation dataset. More precisely, on one hand, the simulation results were evaluated by means of several metrics: the relative error for the simulation inner-domain total precipitation, the percentage of overlapping between the simulated and observed fields for several precipitation thresholds, and the precipitation field area ratio. On the other hand, the simulated and observed precipitation fields were plotted so as to visually appreciate the similarities and differences in the fields' structure and intensity.

It was shown that under an appropriate choice of the model's options and boundary conditions, the WRF model provided satisfactory results in reproducing the location, intensity, and structure of the intense precipitation fields of the historical MCSs. The model's options that were investigated are the parameterization schemes including microphysics, cumulus parameterization, planetary boundary layer physics, long wave and short wave radiation physics, etc. Although certain combinations of the parameterization schemes provided in each case realistic results in terms of the precipitation fields' structures and intensity, placing these fields in the correct spatial locations required additional efforts, so that the best set of model's options varied from one storm system to the other. Second, in this study, a new storm transposition method designed for the transposition of TCs is presented. This method is fully physically based, as it uses a RAM to numerically simulate a TC and its precipitation field. As a result, it has the fundamental advantage of conserving the mass, momentum, and energy in the system since the RAM numerically solves the equations governing the conservation of these quantities. The objective of this method is to find the amount of shift which maximizes the precipitation depth over a given target area. The transposition method was applied to four hurricanes that had spawned torrential precipitation in the United States, namely Hurricanes Floyd (1999), Frances (2004), Ivan (2004), and Isaac (2012). The drainage basin of the city of Asheville, NC was selected as the target. It was observed that the precipitation fields changed in both structure and intensity after transposition. The convergence of the vertically integrated vapor transport (IVT) was found to play a central role in the generation of intense precipitation in these hurricanes.

3.3.2.2.2 Presentation



Plan

1. Extreme precipitation events in the USA
2. Modeling framework
3. Metrics used for model validation
4. Reconstruction of the intense Mesoscale Convective Systems (MCSs)
5. Reconstruction of the intense Tropical Cyclones (TCs)
6. Transposition of the intense TCs
7. Ongoing and future work

Classifications of extreme precipitation events in the USA

- Various classifications of extreme precipitation events in the literature
- In general, a distinction between tropical and non-tropical origin
- Classification proposed by Schumacher and Johnson (2005) and Stevenson and Schumacher (2014):

  ✓ Mesoscale Convective Systems: *convective systems with areal extents greater than 100 km and with durations between 3 and 24 h*

  ✓ Synoptic Systems: *events characterized by the strong large-scale ascent commonly associated with synoptic-scale features (e.g., extratropical cyclones) and/or events lasting longer than 24 h*

  ✓ Tropical Systems: hurricanes and events that are a direct result of a tropical cyclone or its remnants

Objective

Assess the suitability of a regional numerical weather model to

- Simulate local intense precipitation processes, such as MCSs and TCs
- Serve as a test bed for moisture maximization and storm transposition techniques, ultimately updating maximum precipitation estimates and quantifying uncertainty bounds

Selection of intense storms

- We selected 13 TCs and 14 MCSs which generated intense precipitation fields in the USA
  - Hurricane Floyd (1999)
  - Hurricane Isodore (2002)
  - Hurricane Frances (2004)
  - Hurricane Ivan (2004)
  - Hurricane Jeanne (2004)
  - Hurricane Ernesto (2006)
  - Tropical Storm Fay (2008)
  - Hurricane Gustav (2008)
  - Hurricane Irene (2011)
  - Tropical Storm Lee (2011)
  - Hurricane Isaac (2012)
  - Hurricane Sandy (2012)
  - Hurricane Matthew (2016)
  - June 22, 2002 MCS
  - August 22, 2002 MCS
  - September 15, 2004 MCS
  - June 25, 2005 MCS
  - August 17, 2005 MCS
  - September 25, 2005 MCS
  - July 18, 2007 MCS
  - August 19, 2007 MCS
  - June 5, 2008 MCS
  - August 8, 2009 MCS
  - July 23, 2010 MCS
  - September 23, 2010 MCS
  - July 28, 2011 MCS
  - June 22, 2013 MCS
- Intense precipitation events were identified using the website http://schumacher.atmos.colostate.edu/precip_monitor/ from the Precipitation Systems Research Group in Colorado State University
- This website lists every event for which a given threshold (e.g. 100 year, 24 hour) was exceeded for at least one grid cell in the Stage IV precipitation analyses

Plan

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Modeling framework

- We used the Weather Research and Forecasting (WRF) model at 5-km resolution in order to reconstruct the intense precipitation fields

- Climate Forecast System Reanalysis (CFSR) was used for initial and boundary conditions. The provided spatial and temporal resolutions of CFSR are 0.5 x 0.5 degree and 6-hourly

- The WRF model was run in the offline mode: it was only subject to the influence of its initial and boundary conditions, and no observation was used to improve the simulations through nudging or other data assimilation techniques

Modeling framework

• The WRF model was configured to obtain satisfactory results for the simulation of each of the selected severe MCS and TC storm events with respect to the precipitation fields by trying different combinations of the parameterization schemes

- Microphysics
- Cumulus parameterization
- Planetary boundary layer
- Longwave radiation
- Shortwave radiation

• Validation of the WRF model in the offline mode is necessary for the purposes of the project

- Storm transposition (shifting)
- Downscaling of a climate projection from a GCM

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Validation of the results

The results of the WRF model were validated in two ways

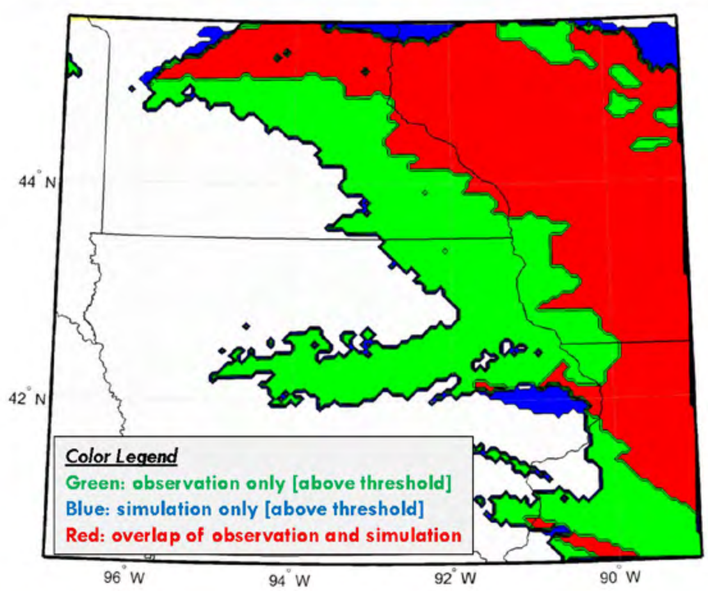
1. The observed and simulated precipitation fields were plotted in order to visually appreciate their similarities and differences, in terms of the fields' position, texture, and intensity

2. Three statistics were used to assess the model's performances
   A. Relative error: indicates if the model could adequately simulate the total precipitation depth over the period of interest

   B. Percentage of overlapping: indicates if the model could place the storm system in the appropriate location

   C. Precipitation field area ratio (PFAR): indicates if the model could properly simulate the size of the precipitation field

Percentage of Overlapping and Precipitation Field Area Ratio (PFAR)



Percentage of Overlapping

$$= \left(\frac{\text{red}}{\text{green} + \text{red}}\right) \times 100$$

$= 54.8\%$

PFAR

$$= \left(\frac{\text{blue} + \text{red}}{\text{green} + \text{red}}\right)$$

$= 0.59$

Best model performance when Percentage of Overlapping is close to 100% and PFAR is close to 1.

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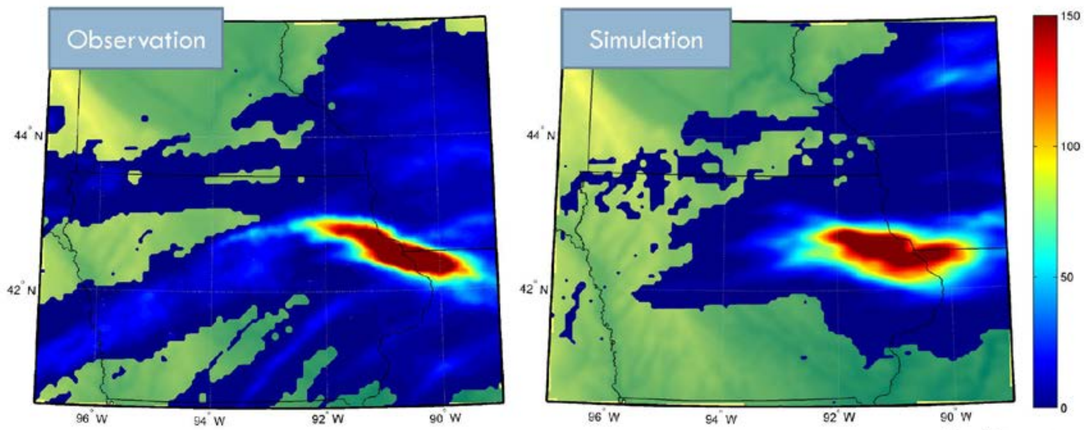
Simulation domains for the Mesoscale Convective Systems

Two nested domains were set up for the WRF numerical simulation so that the inner domain covers an area where intense precipitation is frequently caused by Mesoscale Convective Systems

1. Domain 1 (purple) is the outer, parent domain. It has a resolution of 15 km (76 x 58)
2. Domain 2 (light blue) is the inner, nested domain. It has a resolution of 5 km (166 x 118)

July 28, 2011 Mesoscale Convective System

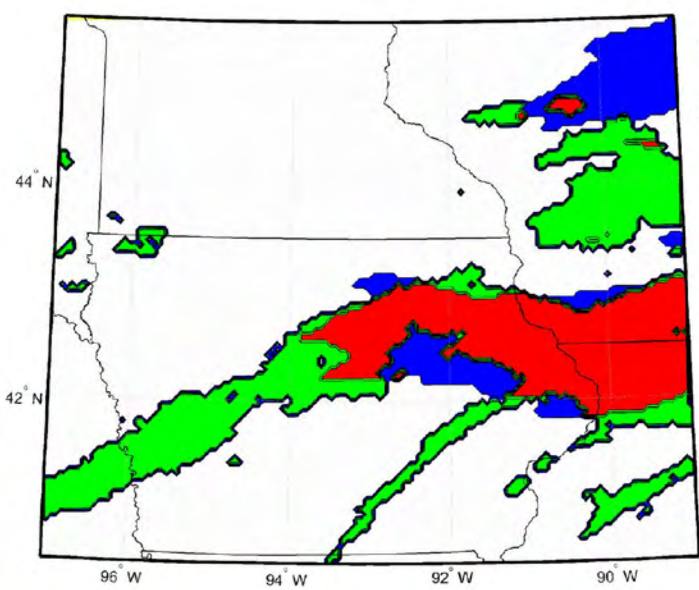
Total precipitation computed from
07/27/2011 at 15:00 to 07/28/2011 at 15:00



The relative error was computed to be -7.0%

July 28, 2011 Mesoscale Convective System

For the 75th percentile (9.09 mm)



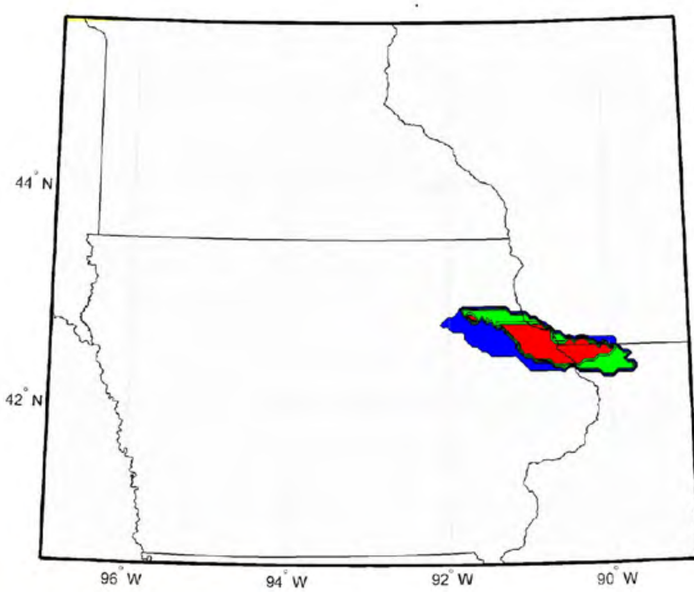
Percentage of Overlapping = 42.5%

PFAR = 0.66

Color Legend
Green: observation only
Blue: simulation only
Red: overlap

July 28, 2011 Mesoscale Convective System

For the 99th percentile (132.63 mm)



Percentage of Overlapping = 61.7%

PFAR = 1.14

Color Legend

Green: observation only

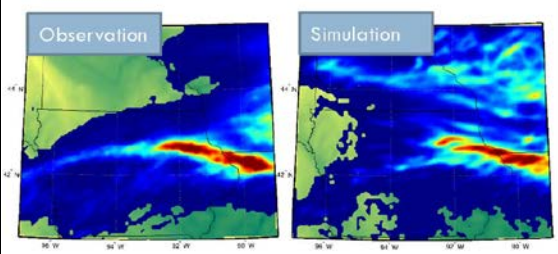
Blue: simulation only

Red: overlap

Overview of additional reconstructed Mesoscale Convective Systems

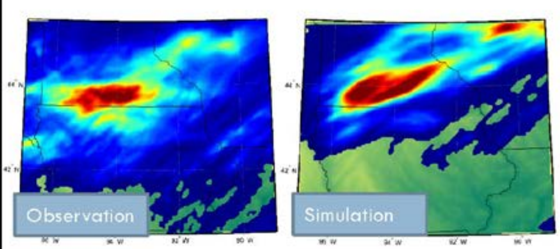
July 23, 2010 MCS

07/22/2010 at 18:00 to 07/23/2010 at 18:00



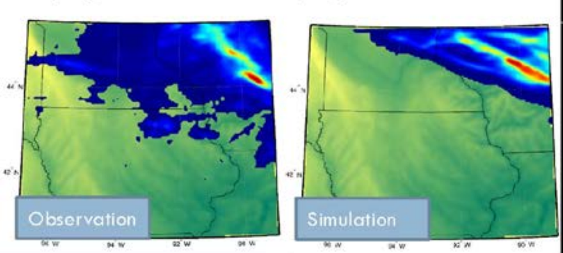
September 25, 2005 MCS

09/24/2005 at 21:00 to 09/25/2005 at 21:00



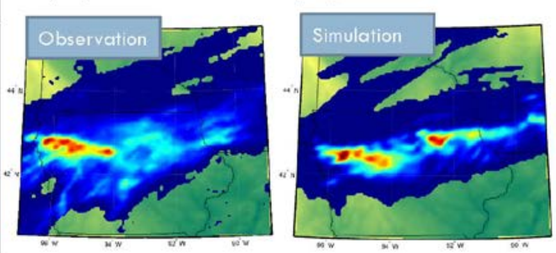
June 22, 2002 MCS

06/21/2002 at 19:00 to 06/22/2002 at 19:00



June 25, 2005 MCS

06/24/2005 at 18:00 to 06/25/2005 at 18:00



Reconstruction of intense Mesoscale Convective Systems

- Visually comparing the observation and simulation figures shows that the MCSs simulated by the WRF model are quite similar in shape, texture, and location to the MCSs shown on their corresponding observation figures
- The three statistics computed for each event also revealed that the WRF model simulated the total precipitation depth, the location of the storm, and the field size adequately well for all the MCSs
- The WRF model was capable of reproducing all the selected intense MCSs very well under the appropriate model parameterization schemes

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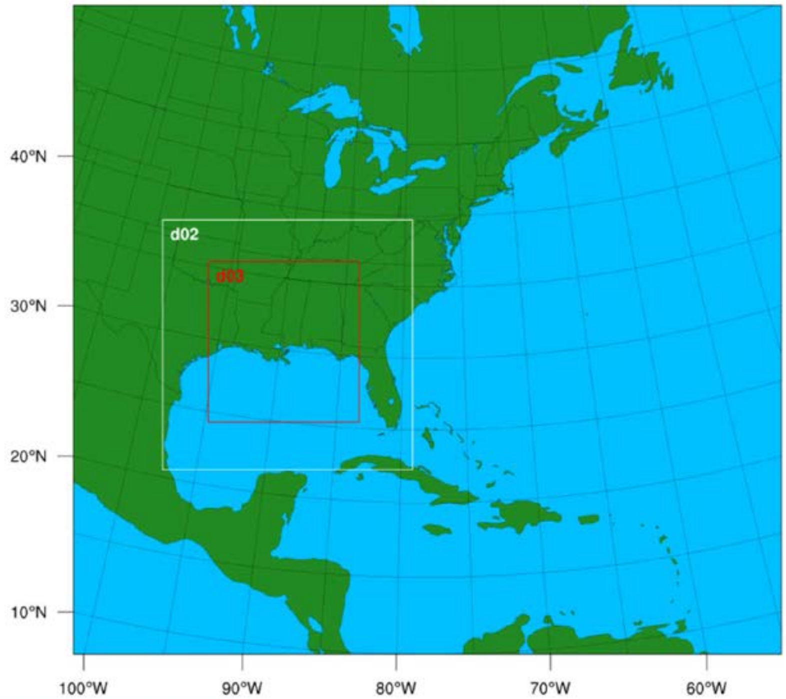
6. Transposition of the intense TCs
7. Ongoing and future work

Simulation nested domains for Hurricane Isaac (2012)



- Domain 1 (same for all storms):

45 km resolution
120 x 110

- Domain 2:

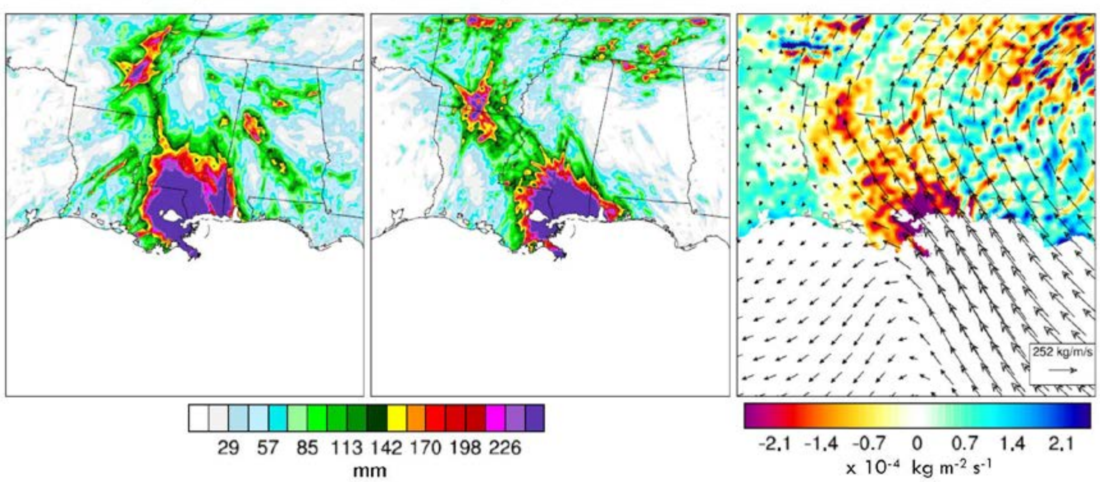
15 km resolution
127 x 127

- Domain 3:

5 km resolution
229 x 244

Hurricane Isaac (2012)

Observed precipitation field | Simulated precipitation field | IVT and its divergence



	50th percentile		75th percentile		90th percentile		95th percentile		97.5th percentile		99th percentile	
Relative Error	% overlap	PFAR	% overlap	PFAR	% overlap	PFAR	% overlap	PFAR	% overlap	PFAR	% overlap	PFAR
-13%	56%	0.87	49%	0.94	53%	0.84	56%	0.72	40%	0.79	26%	1.27

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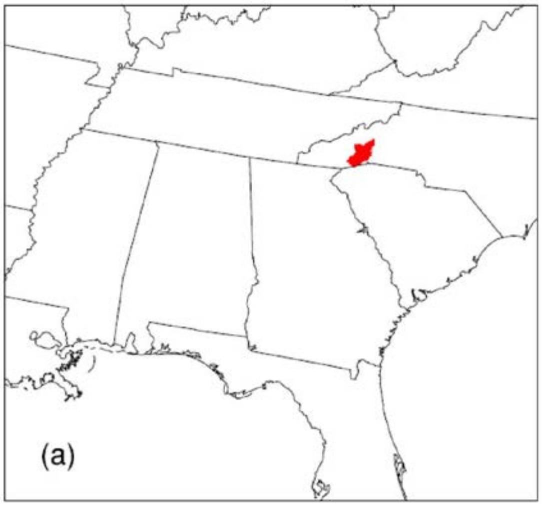
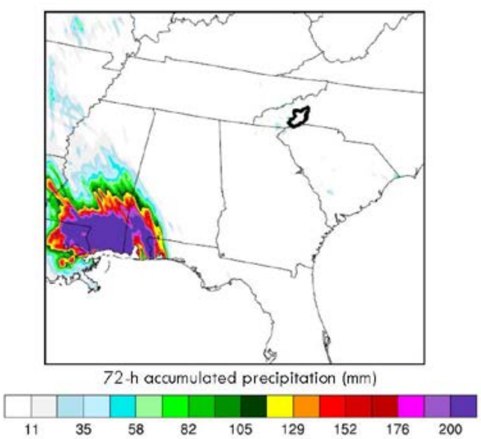
7. Ongoing and future work

Storm transposition of Tropical Cyclones

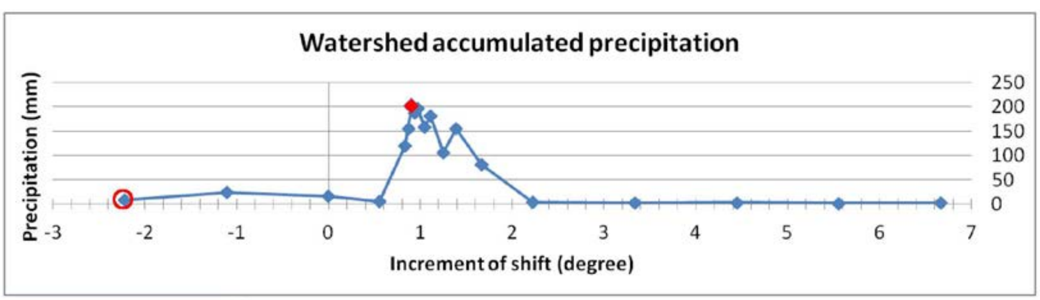
- We developed a new fully physically based method for the storm transposition (i.e. shifting) of TCs.
- The objective of this method is to find the amount of shift which maximizes the precipitation depth over a given target area.
- It uses a regional atmospheric model (RAM) to numerically simulate a TC and its precipitation field. As a result, it has the fundamental advantage of conserving the mass, momentum, and energy in the system since the RAM numerically solves the equations governing the conservation of these quantities.

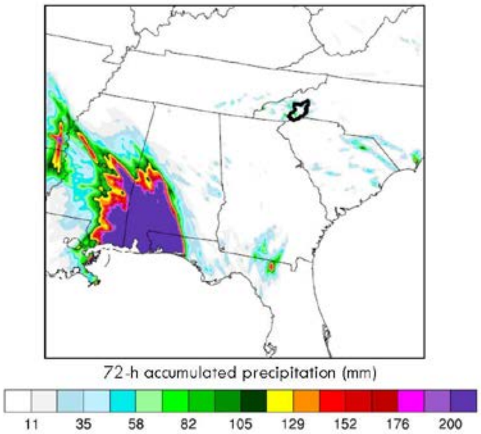
Target area



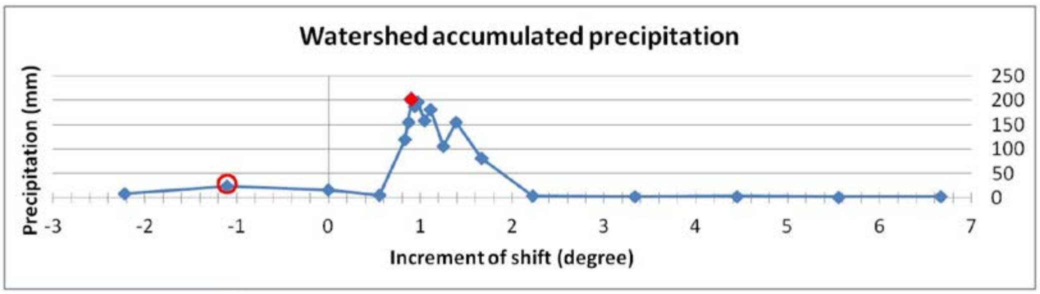


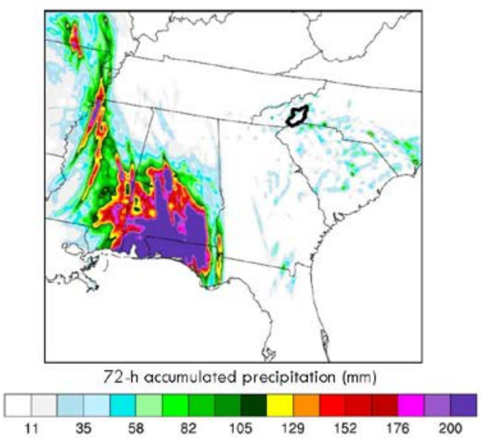
Precipitation	8 mm
WE Shift	-1.57 degrees
SN Shift	-1.57 degrees
Start Date	08/29 21h
End Date	09/01 21h



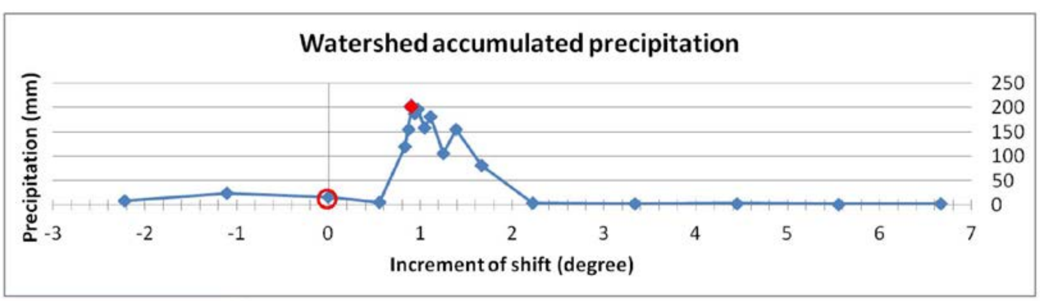


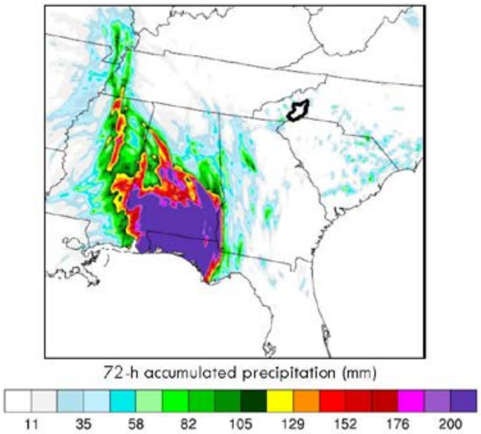
Precipitation	24 mm
WE Shift	-0.79 degrees
SN Shift	-0.79 degrees
Start Date	08/28 17h
End Date	08/31 17h



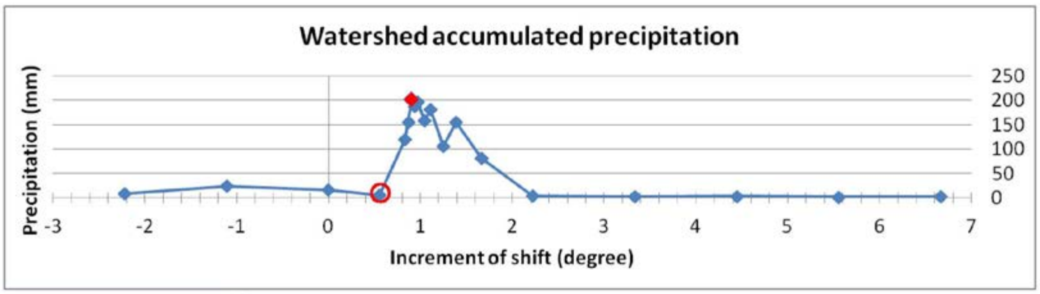


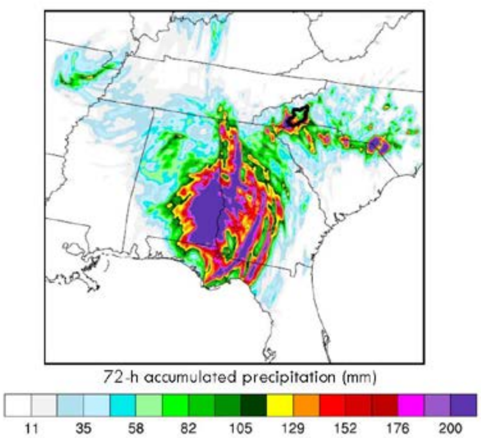
Precipitation	16 mm
WE Shift	0 degrees
SN Shift	0 degrees
Start Date	08/29 03h
End Date	09/01 03h



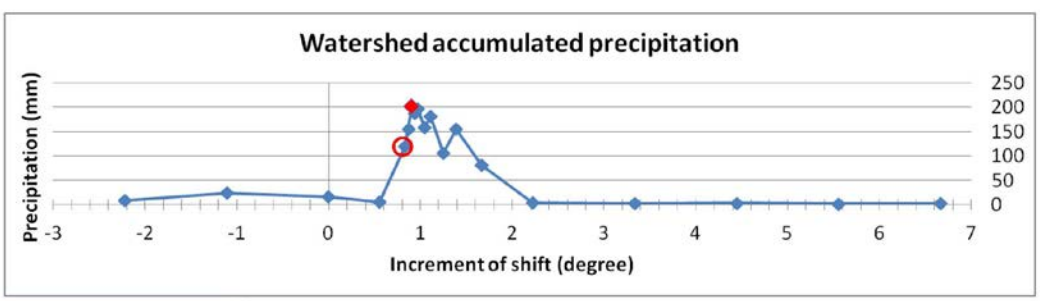


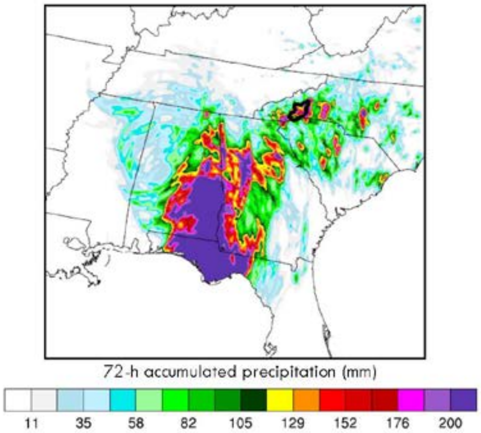
Precipitation	6 mm
WE Shift	0.39 degrees
SN Shift	0.39 degrees
Start Date	08/28 22h
End Date	08/31 22h



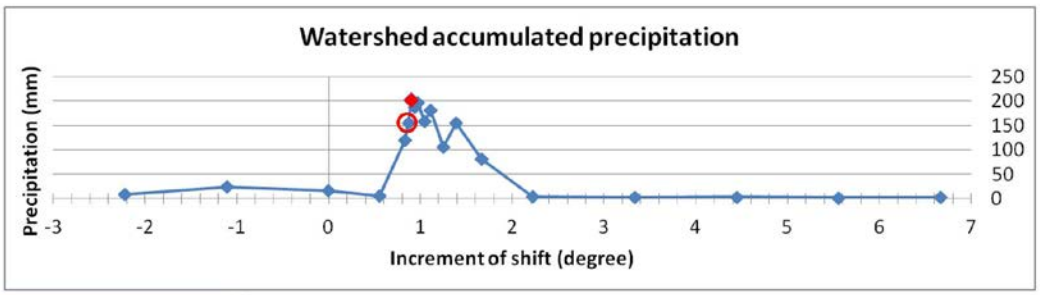


Precipitation	119 mm
WE Shift	0.59 degrees
SN Shift	0.59 degrees
Start Date	08/29 11h
End Date	09/01 11h

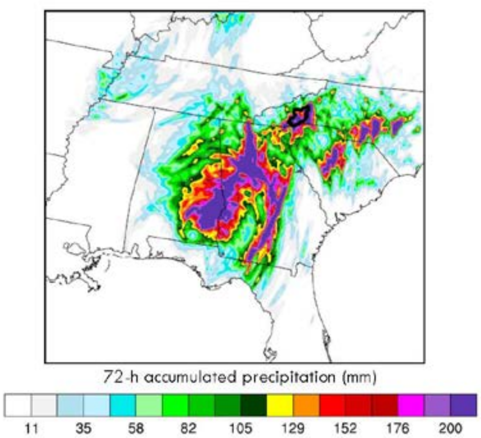




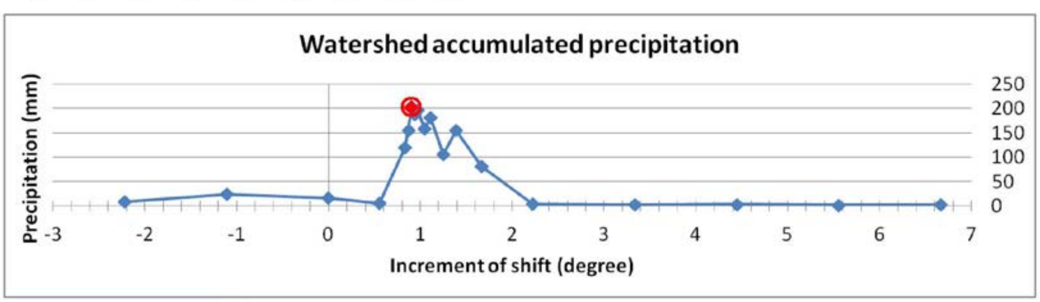
Precipitation	155 mm
WE Shift	0.61 degrees
SN Shift	0.61 degrees
Start Date	08/28 16h
End Date	08/31 16h

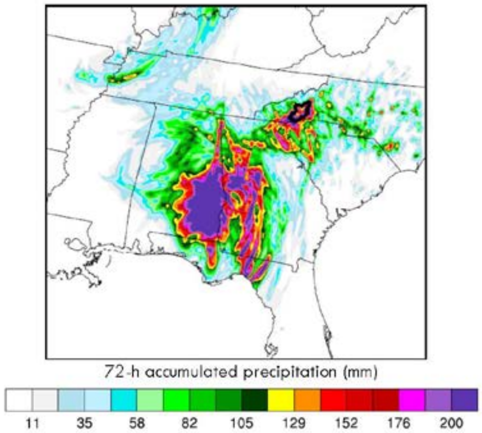


"Maximum"

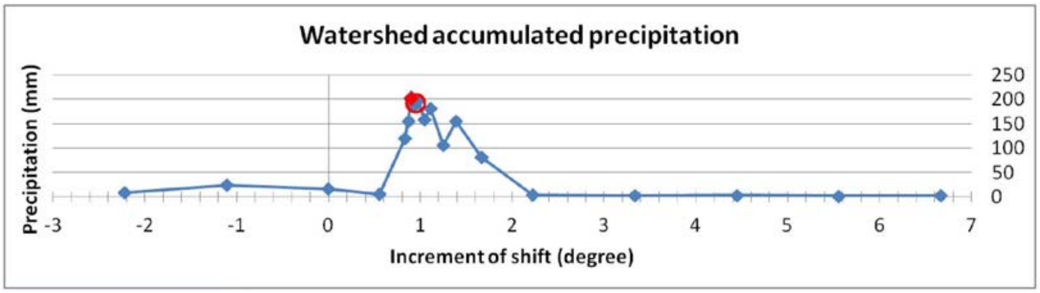


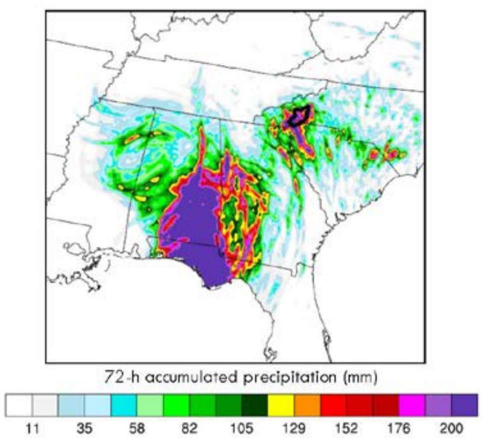
Precipitation	202 mm
WE Shift	0.64 degrees
SN Shift	0.64 degrees
Start Date	08/29 12h
End Date	09/01 12h



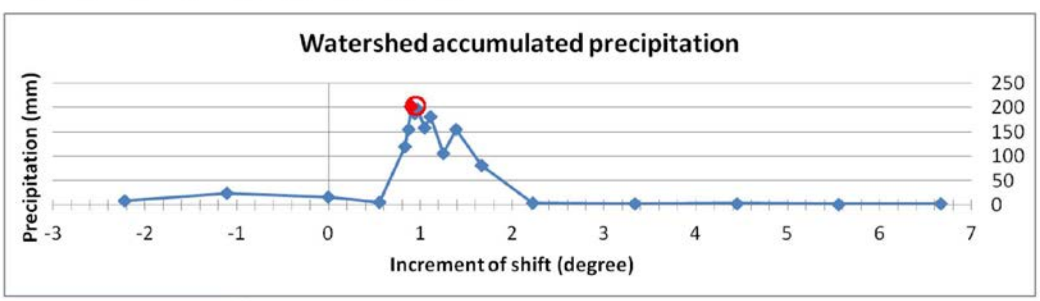


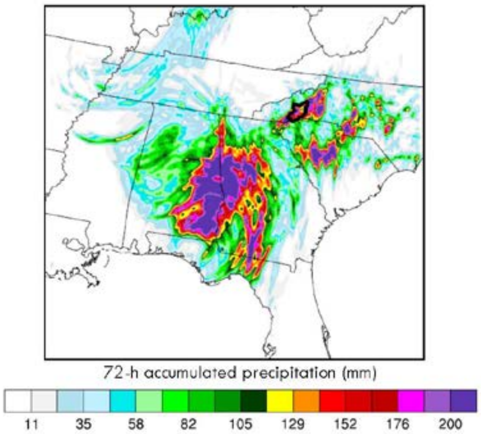
Precipitation	188 mm
WE Shift	0.66 degrees
SN Shift	0.66 degrees
Start Date	08/29 12h
End Date	09/01 12h



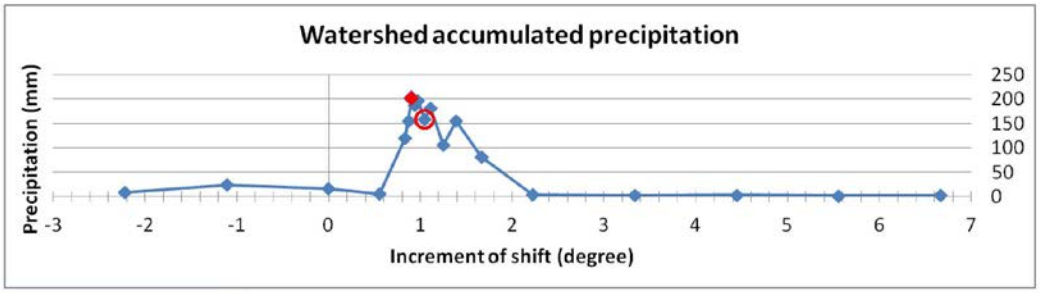


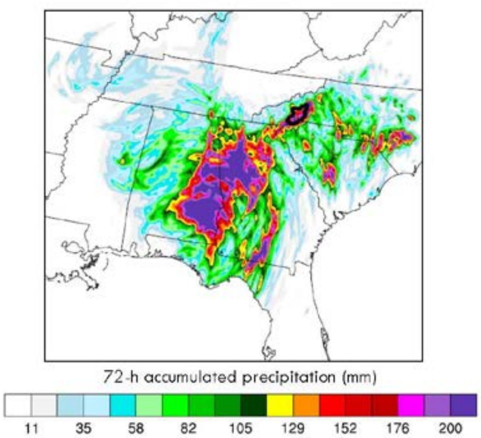
Precipitation	197 mm
WE Shift	0.69 degrees
SN Shift	0.69 degrees
Start Date	08/28 17h
End Date	08/31 17h



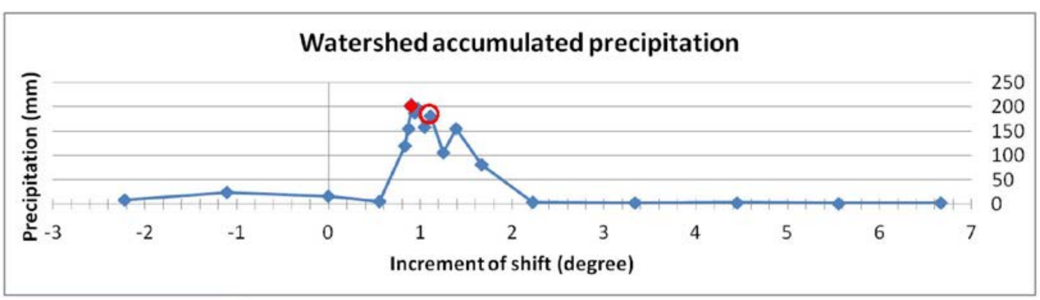


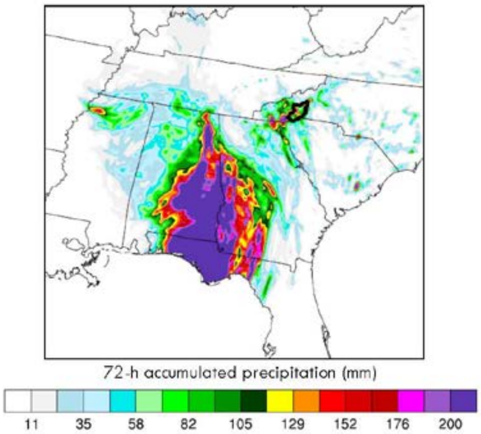
Precipitation	158 mm
WE Shift	0.74 degrees
SN Shift	0.74 degrees
Start Date	08/29 12h
End Date	09/01 12h





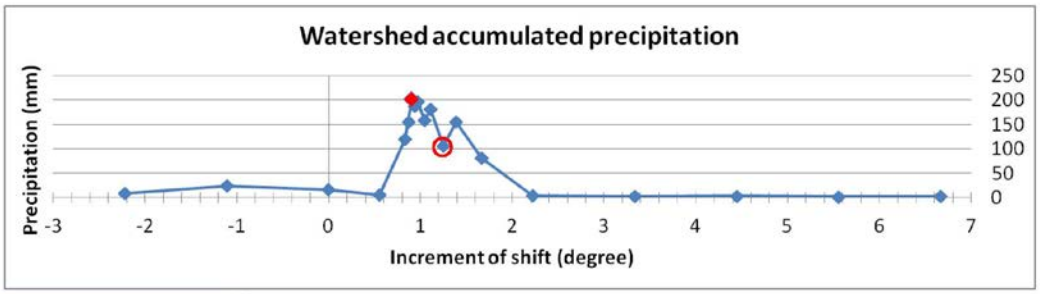
Precipitation	181 mm
WE Shift	0.79 degrees
SN Shift	0.79 degrees
Start Date	08/29 08h
End Date	09/01 08h

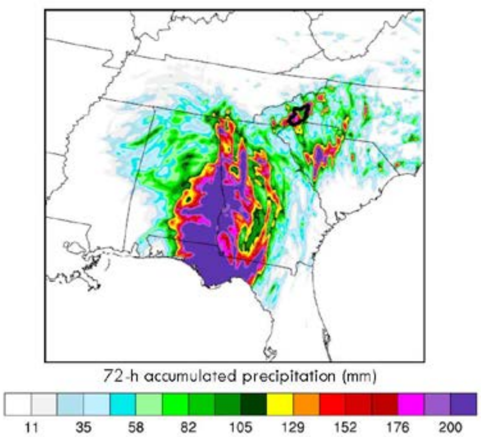




72-h accumulated precipitation (mm)

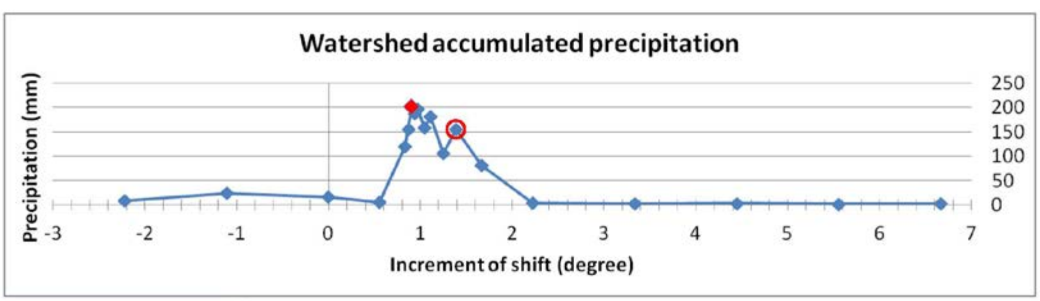
Precipitation	106 mm
WE Shift	0.88 degrees
SN Shift	0.88 degrees
Start Date	08/28 16h
End Date	08/31 16h

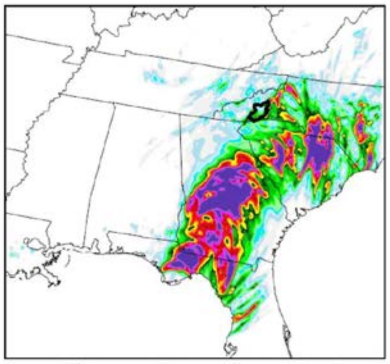




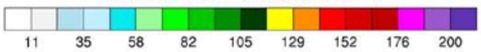
72-h accumulated precipitation (mm)

Precipitation	155 mm
WE Shift	0.98 degrees
SN Shift	0.98 degrees
Start Date	08/28 17h
End Date	08/31 17h

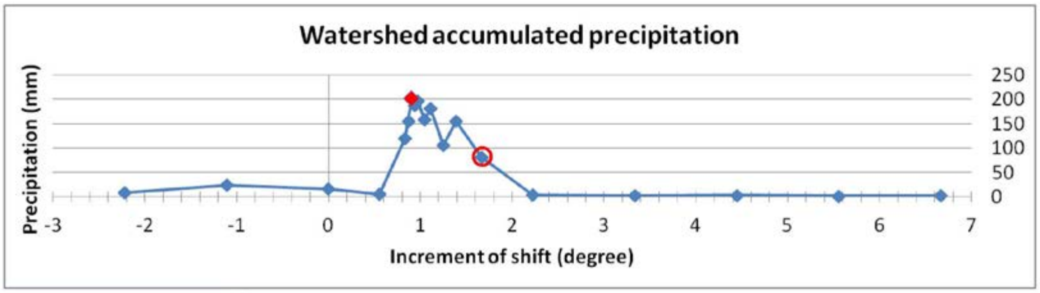


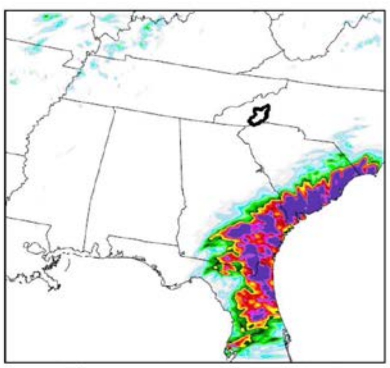


72-h accumulated precipitation (mm)

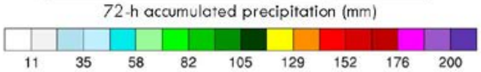


Precipitation	80 mm
WE Shift	1.18 degrees
SN Shift	1.18 degrees
Start Date	08/29 02h
End Date	09/01 02h

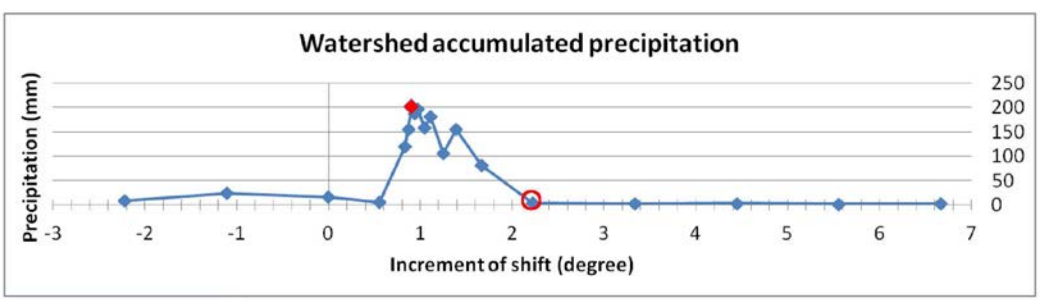


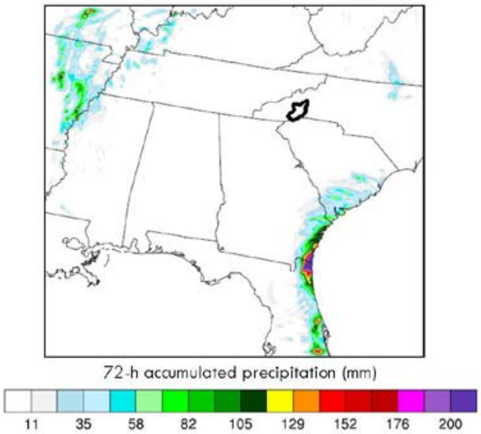


72-h accumulated precipitation (mm)

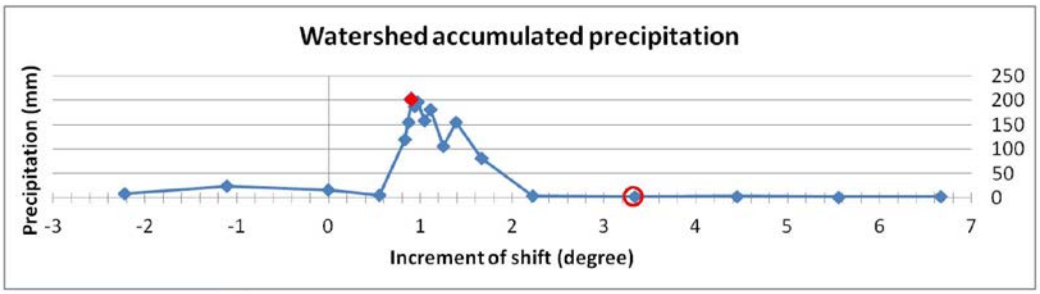


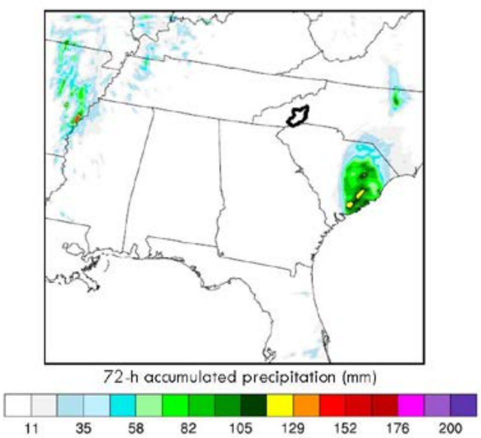
Precipitation	4 mm
WE Shift	1.57 degrees
SN Shift	1.57 degrees
Start Date	08/26 23h
End Date	08/29 23h



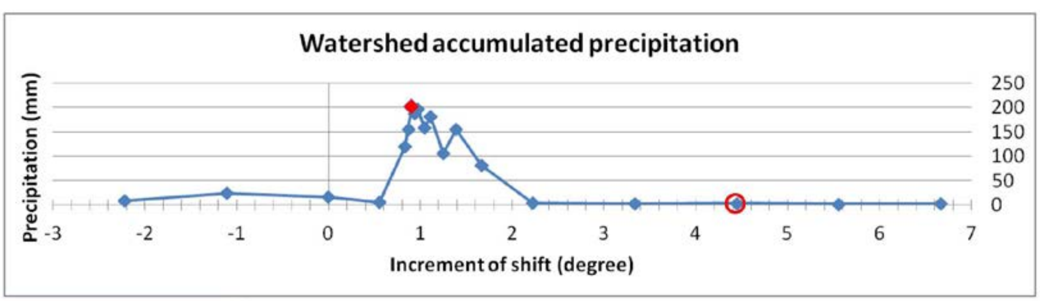


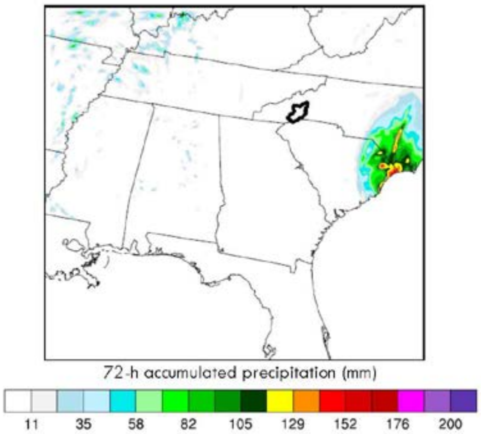
Precipitation	2 mm
WE Shift	2.36 degrees
SN Shift	2.36 degrees
Start Date	08/25 10h
End Date	08/28 10h



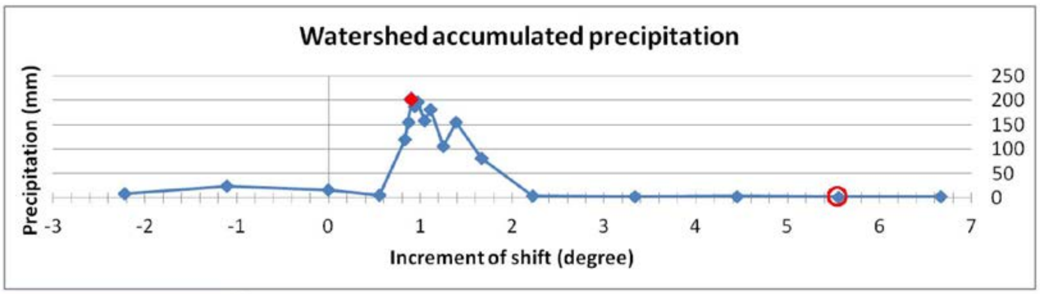


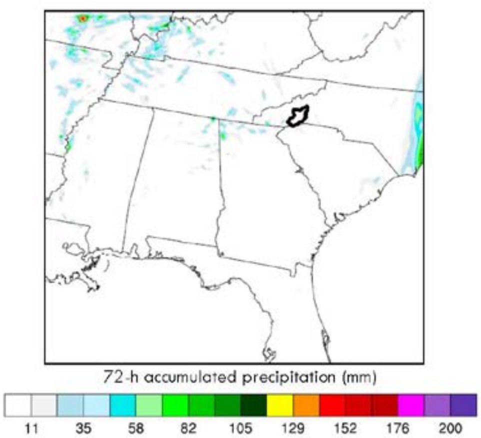
Precipitation	3 mm
WE Shift	3.15 degrees
SN Shift	3.14 degrees
Start Date	08/25 06h
End Date	08/28 6h



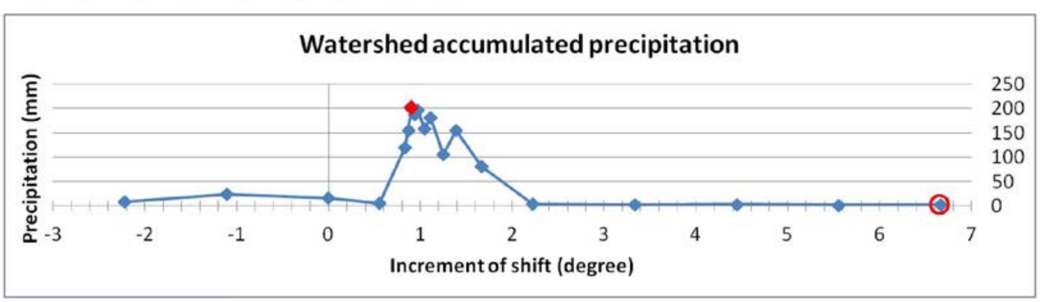


Precipitation	2 mm
WE Shift	3.93 degrees
SN Shift	3.92 degrees
Start Date	08/25 22h
End Date	08/28 22h





Precipitation	2 mm
WE Shift	4.72 degrees
SN Shift	4.71 degrees
Start Date	08/25 22h
End Date	08/28 22h

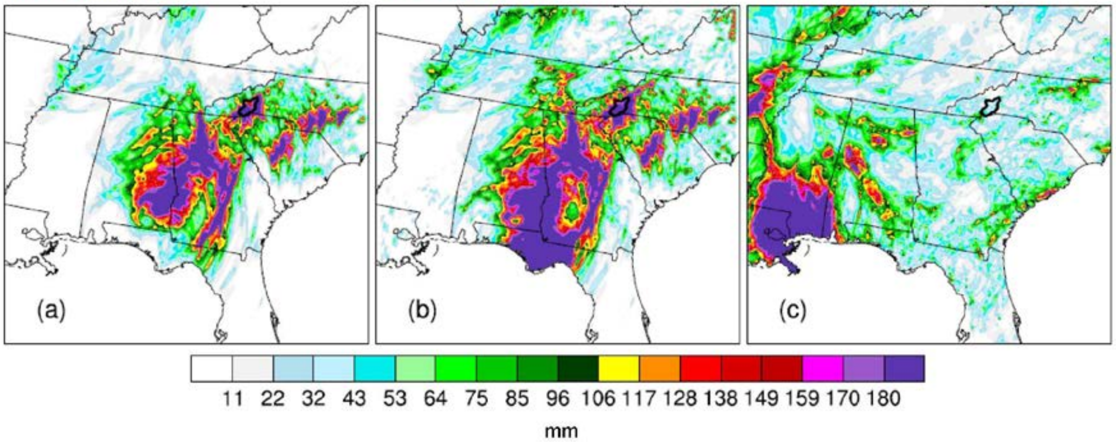


Transposition of Hurricane Isaac (2012)

Maximized 3-day accumulated precipitation field

Maximized 7-day accumulated precipitation field

Observed 7-day accumulated precipitation field

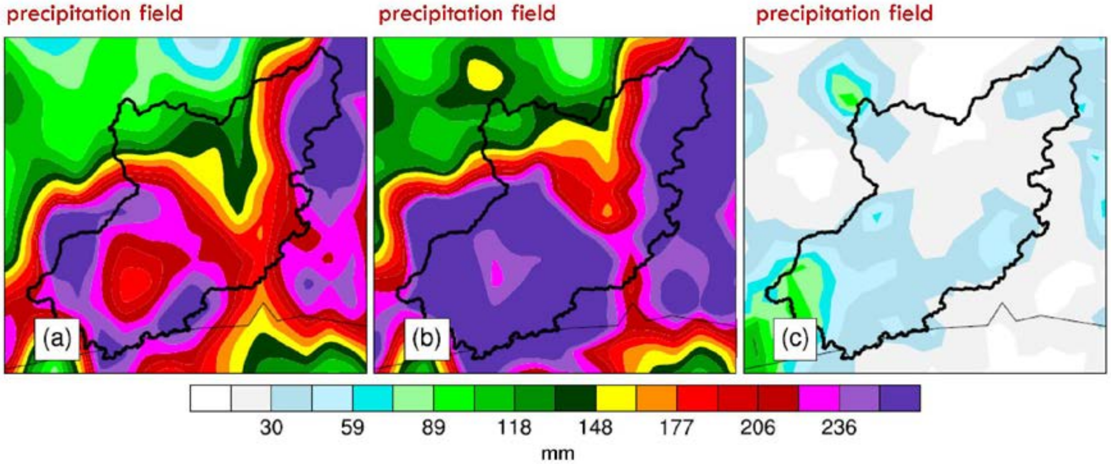


Zoom over target area

Maximized 3-day accumulated precipitation field

Maximized 7-day accumulated precipitation field

Observed 7-day accumulated precipitation field

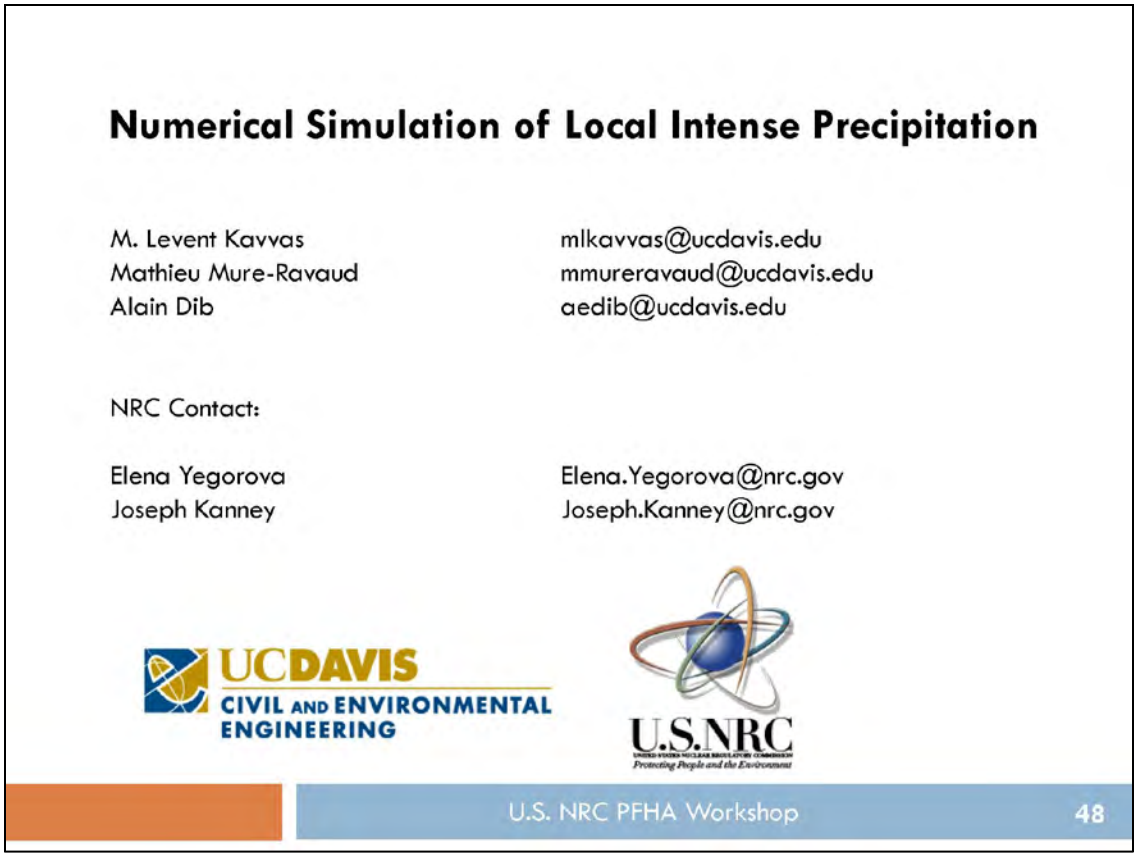


Plan

1. Extreme precipitation events in the USA
2. Modeling framework
3. Metrics used for model validation
4. Reconstruction of the intense Mesoscale Convective Systems (MCSs)
5. Reconstruction of the intense Tropical Cyclones (TCs)
6. Transposition of the intense TCs
7. **Ongoing and future work**

Ongoing and future work

- Perform the storm transposition exercise for one MCS
- Determine the most intense future storm for each region (for the two storm types) using the Community Climate System Model version 4 (CCSM4) climate projection, and perform transposition of these 2 storms



3.3.2.2.3 Questions and Answers:

Question: The first one is with your TC simulation. You showed some statistics there such as overlap per percentage and so on. You indicated that you felt those results were quite good. I'm just wondering, the statistics certainly are very useful that you use, but in terms of judging the acceptability of the simulation, it would seem like you'd need to sort of evaluate your simulation in the context of how that information is going to be used. In order to know if the errors in the simulation are acceptable, in terms of that application. That's the first question. Second question is a lot simpler. With your transposition approach, have you considered incorporating uncertainty into that approach?

Response: For the first question regarding the quality of the simulation, we tried hundreds of combinations of the parameterization schemes and I don't know how many of you are familiar with the numerical modeling of some system but it's extremely complicated. For those who are familiar with such modeling, you will know that these results are actually quite satisfactory. So, the idea is we want to estimate, in the case of the storm transposition exercise, what would have been the precipitation that's over a given target area. The first step is always to validate the model before using the model in order to make an estimation. So, this is what was done in the first step -to calibrate and validate the worst model. Of course, for the results that we obtained, in the perspective of the quality of the calibration, there was for example minus 13 percent relative error and the other statistics are not perfect, but we can still say that the estimation that we obtained is relevant. Now coming to the second question regarding the uncertainty, if I remember the uncertainty for the storm transposition, there would be several ways to tackle this issue, for example, one could use several combinations of the parameterization schemes. Meaning that in this case we show the results for one combination which was assessed to be the best combination. One could use several combinations with which are assessed to be satisfactory and do the transposition exercise with all the combinations which would give several estimations of the maximum precipitation about the targets. And one would obtain some uncertainty related to the model based on these different values that are obtained by using the different combinations. Also, one could try to use different data sets for the initial and boundary conditions. Also, one could do the exercise for the Quebec projections so there are many climate projections. In this case we used only one start date for the simulation. One could use many start dates for the simulation, so there are several ways that one could tackle uncertainties of the model, of the boundary initial conditions, and so on.

Question: Kelly Mahoney, by how much does the storm environment change in the RAM based shifting procedure?

Response: So, in the middle you can see that the drainage basin is located in a mountainous area, while in the observed case, the historical system affected a region which is not mountainous. So is a very significant change in topography first of all. Then I'm not familiar with the land surface issue, but if there was a tremendous difference between the location of the historical system and the location of the maximized system.

Question:

John England from USACE, we struggle with transposition so I'm wondering if you have had the opportunity to start to place a hierarchy on particularly the tropical cyclones in how far you start to move them. The example I'm going to ask is if you look at Agnes and you go extra-tropical and the source is the Gulf and it recurves to the Atlantic and zooms back into Pennsylvania, Western Pennsylvania particularly, your transposition area might be determined by the tract or other features from maybe a library of TC tracks.

Response:

So, the technical details regarding how the transposition was performed will be given in the final reports. But the storm transposition can be performed in any conditions. If the storm transposition is legitimate or not –that's another question. For the legitimacy of the storm transposition, there are a certain number of criteria that need to be met. For example, for the storm transpositions you mentioned, I think an extra-tropical transition, if the storm has already started the historical transition, the shifting of the storm is not necessarily legitimate, except if the amount of shift is very small. You cannot put back into the Atlantic Ocean a storm which already started to interact with the land and with other systems in the mid-latitudes. So, all these criteria will be listed in the final report for this project.

Question:

Just to clarify, when you do the transposition, the broad moisture field stays the same, you're just moving the track? Correct?

Response:

Yes. We transpose this storm –not the overall field.

Question:

Just kind to get an idea of the levels effort to do these WRF simulations of these transformed storms, and if you did put this into a stochastic framework to get a better idea of uncertainty, what kind of level of computational time which you need?

Response:

With today's technologies such exercises are possible. In the case of the tropical cyclone, it is different from what has been done in the past by Professor Kavvas and his team. For example, for atmospheric rivers in which case there was a two-dimensional search for the maximum. In the case of tropical cyclone, what you can do is if the storm is moving in this direction can just shift it that way. There is no need to shift in the direction of the storm. So, in this case it is just possible to do a one-dimensional search which considerably limits the computational efforts but it's still quite demanding.

Question:

Bill Kappel, I'll make it quick hopefully. Just a quick question on this. When we talk about transposition ability, so Hurricane Isaac is a direct hurricane with landfall and coastal interaction processes. And there’s really no topography over Louisiana, Mississippi, and Alabama. But when it moved to the Asheville Basin, how did WRF take into account the differences in topography and moisture sources? When we talk about transpositioning storms, one of the key definitions is that they need to be moved within similar regions of meteorology and topography. Obviously New Orleans is a lot different than Asheville, North Carolina. So how do you determine where to test and move these storms? And then, if so, how do you parameterize the model differently for the two locations?

Response:

As far as I am familiar with the traditional PMP approaches, what was done is to shift the precipitation field module adjustments. In this case, you can see that the shifted precipitation field is fundamentally different from the original precipitation field. If I remember from the traditional PMP approach, they consider this region of homogeneity for the transposition of the precipitation field. In this case, we only manipulated the initial and the boundary conditions and the model is run as normal. I mean once this manipulation has been made, the model is run as usual and all the interactions are taken into account. I think the second part of your question was for the validity of the parameterization schemes. The fact that the model was calibrated for a given region and affects another region. Is the combination of the scheme adapted for the new region? I think it is an important point and these we will need to investigate but as we mentioned earlier for a previous question, the fact to use several combinations of parameterization schemes in order to account for uncertainties would also affect this issue of is one given combination adapted for a new region of the country. So, using several combinations would really be beneficial also for this problem.

Question:

Kelly Mahoney , is the best combination of model physics the same across all simulations or is the best simulation chosen individually for each storm?

Response:

The best combination because there are several millions of possible combinations in the WRF model. We looked for a satisfactory combination so it's not an optimization exercise properly speaking. There was an algorithm to find the best combination. We looked for a satisfactory combination and the satisfactory combination changes from one tropical cyclone to another. But for a given tropical cyclone, the combination was the same between the calibration and the functions position.

3.3.2.3 Research on Extreme Precipitation Estimates in Orographic Regions Kathleen Holman^, Andrew Verdin, and David Keeney, Flood Hydrology and Meteorology Group, Technical Services Center, U.S. Bureau of Reclamation (Session 2B-3; ADAMS Accession No. ML17355A087)

3.3.2.3.1 Abstract

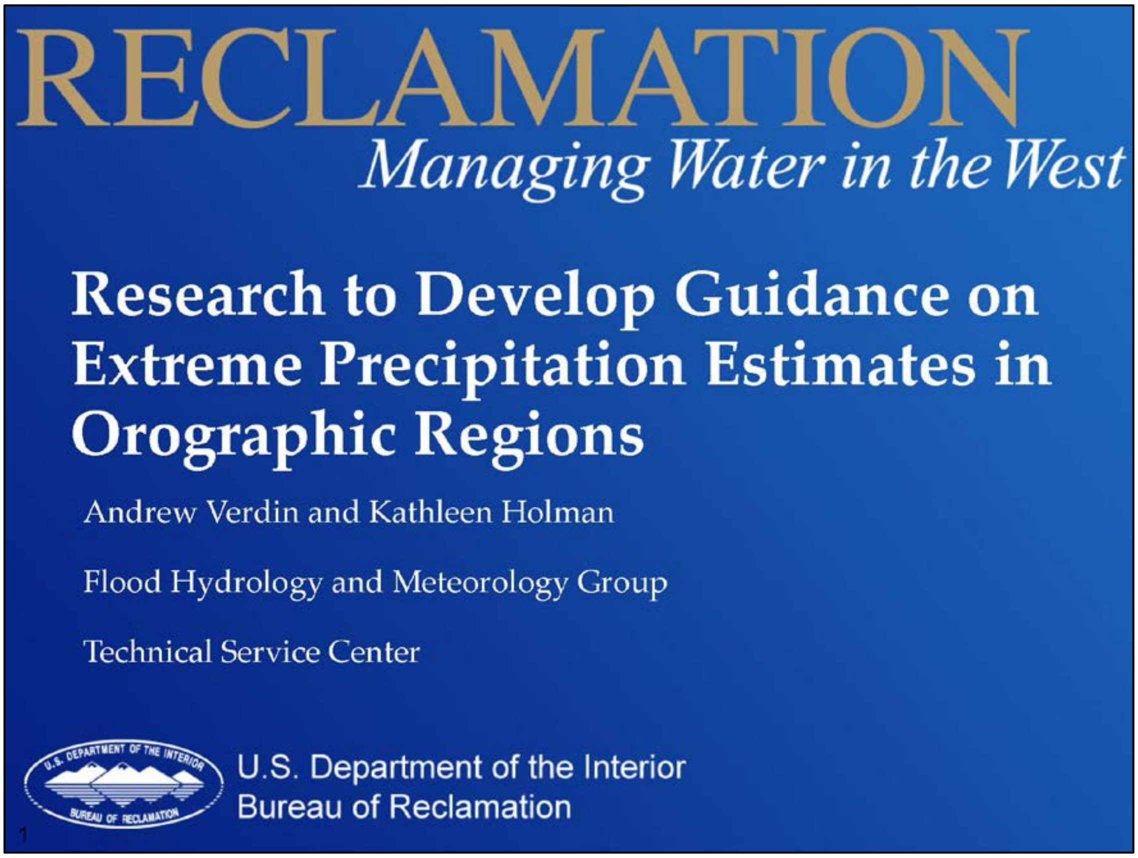
We present the findings of the research project “Phase II: Research to Develop Guidance on Extreme Precipitation. Frequency Estimates for the Tennessee Valley.” The definitive objectives of this research project are: (i) Review extreme storm precipitation techniques, precipitation-frequency methods, and databases in orographic regions; (ii) Develop a methodology to estimate precipitation-frequency in regions of complex topography; and (iii) Demonstrate the precipitation-frequency methodology and provide uncertainties and confidence intervals at the regional and reactor-site scale for a pilot region in the Tennessee River Valley watershed (TRVW). The focus of this presentation is on the development of a generalized framework for precipitation-frequency analysis in orographic regions. Obtaining reliable precipitation-frequency estimates requires confidence in the estimated extreme value distribution parameters. However, parameter estimation is sensitive to a number of influential factors, the period of record being critical. Regional frequency analysis (RFA) is a commonly used technique for extending the period of record, using a “space-for-time” substitution method. The fundamental basis of RFA is the assumption that observations from climatically similar stations can be described by the same probability distribution.

The methodology developed in this research combines a known objective clustering algorithm, the Self-Organizing Map (SOM), with two distinct frequency estimation methods, L-moments and Bayesian inference . The SOM algorithm utilizes a combination of geophysical information and observed precipitation data to identify climatically similar groups of stations (i.e., homogeneous regions, hereafter HRs) within the TRVW. L-moments and Bayesian inference are then used to estimate generalized extreme value (GEV) distribution parameters to produce regional growth curves (RGCs) for each of the HRs. Site-specific precipitation-frequency estimates are obtained by scaling the RGCs by the at-site mean for the site of interest. Only the GEV distribution was considered, as epistemic uncertainty due to probability distribution choice was not the focus of this research. Results suggest that uncertainty estimates from the L-moments analysis are consistently less than the uncertainty estimates from Bayesian inference. These differences are the result of estimating uncertainty differently between the two methods.

It may be of interest to produce precipitation-frequency estimates at locations where no historical data are available. To this end, we illustrate the benefit of using a gridded precipitation dataset as

input to RFA. Specifically, the Newman et al. (2015) dataset contains an ensemble of gridded daily precipitation for 33 years at 1/8-degree resolution. The ensemble contains 100 members, each of which are equally plausible precipitation totals for the grid cell of interest. We illustrate how the ensemble members are collapsed into a single dataset, and the extreme value distribution parameters are estimated independently at each grid cell. This presentation ends with an illustration of the two methods' abilities in quantifying small exceedance probability precipitation events with associated uncertainty.

3.3.2.3.2 Presentation



Outline

- Motivation
- Precipitation-Frequency analysis
  - Frequency Analysis Methods
  - Datasets
- Case study in Tennessee River Valley
  - L-moments
  - Bayesian
- Summary & Conclusions

2

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Motivation

3

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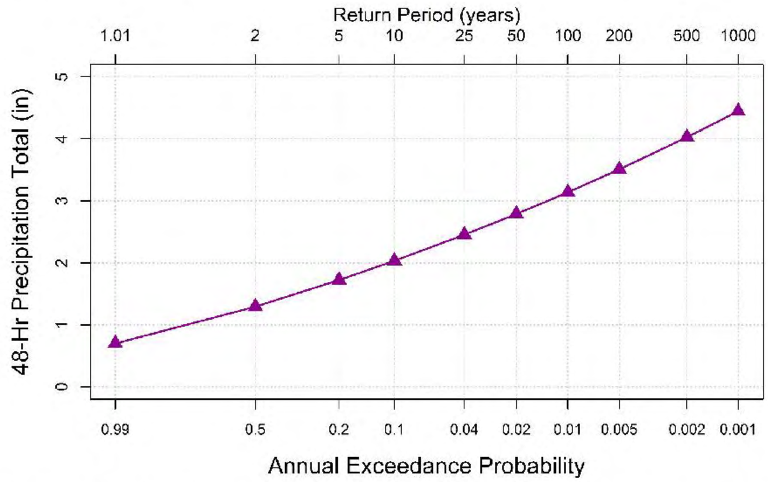
Motivation

Q: What is a precipitation-frequency relationship?



A: Statistical relationship relating precipitation depth to the probability of exceeding that depth.

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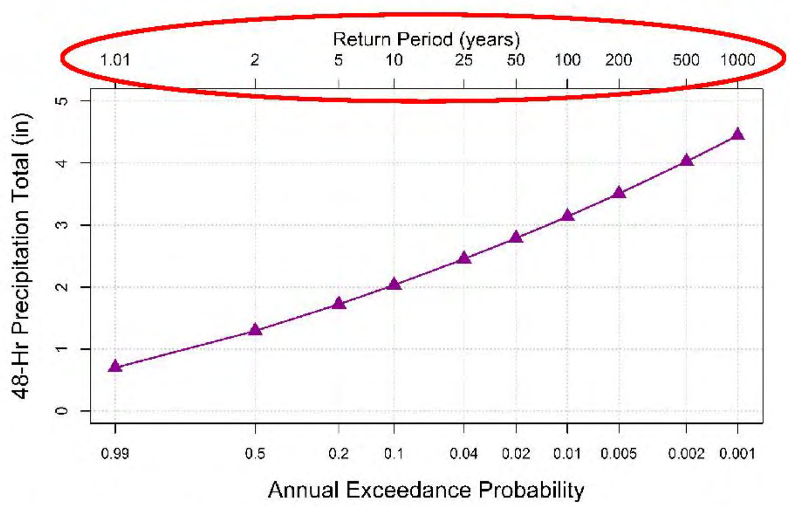
4

Motivation

Probability reported as "return period" or "average recurrence interval"



Return period of: 100 years means the probability is 1-in-100 (0.01)
500 years means the probability is 1-in-500 (0.002)
1,000 years means the probability is 1-in-1000 (0.001)

5

Precipitation-Frequency Analysis

Define relevant precipitation duration

→ e.g., 1-day, 2-day, etc.

Extract annual/seasonal maxima from daily time series

QC annual/seasonal maxima for false maxima

Fit extreme value distribution to maxima

→ Estimate $\theta = (\mu, \sigma, \xi)$

Calculate quantiles of distribution

→ Precipitation magnitudes and associated probabilities

6 RECLAMATION

Regional Frequency Analyses

Assume observations within homogeneous region (HR) described by single distribution

→ Pool all annual/seasonal maxima within HR

Scale the annual/seasonal maxima by the at-site mean of the maxima

→ Mean at each site -> 1

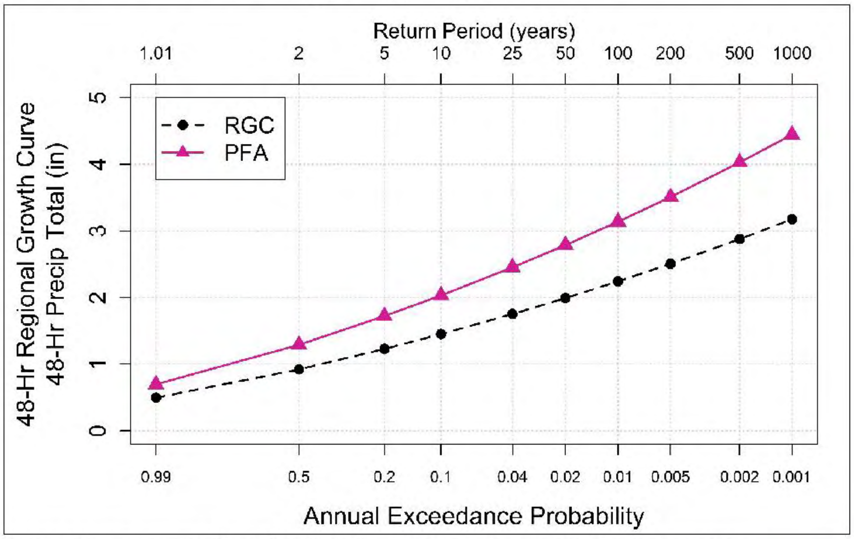
Compute precipitation-frequency relationship, produce regional growth curve (RGC)

→ Scale by specific at-site mean for point estimates

7 RECLAMATION

Regional Growth Curve

Unitless curve describing all gauges in HR



Scale by site-specific ASM for site-specific PF curve

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8

Frequency Analysis Methods

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9

L-moments

10

RECLAMATION

L-Moments

- Developed for ***regional*** frequency analysis
- Identify weather stations (sites) within HR
- Screen observations
  - annual/seasonal/monthly maxima
  - duration depends on meteorology
- Quality control data
- Compute L-statistics* for each site
  - L-mean, L-scale, L-skewness, L-kurtosis
- Test for heterogeneity
  - Discordancy measures (e.g., $D_i \leq 3$)
- Identify the "best" distribution
  - GEV, GPD, GNO, GLO, PE3, Wakeby
- Calculate regional growth curve (weighted by POR)
  - Scale growth curve (point, basin, region)

Available R packages for L-moments:
library("lmom")
library("lmomRFA")

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L-statistics

Alternative system of describing probability distribution functions based on linear combinations of moments

L-moments:

λ_1=L-location (mean)

λ_2=L-scale (variability or dispersion)

λ_3=L-skewness (asymmetry)

λ_4=L-kurtosis (thickness of tail)

L-moment ratios (dimensionless):

$T_r=\lambda_r/\lambda_2$

T=L-CV= λ_2/λ_1 (variability)

Hosking and Wallis (1997)

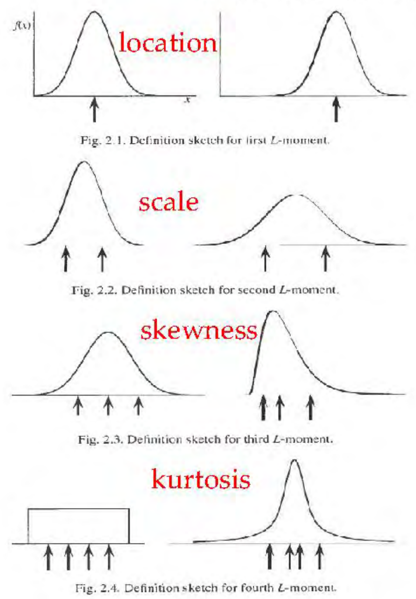

Fig. 2.1. Definition sketch for first L-moment.
Fig. 2.2. Definition sketch for second L-moment.
Fig. 2.3. Definition sketch for third L-moment.
Fig. 2.4. Definition sketch for fourth L-moment.

Available R packages for L-moments:
library("lmom")
library("lmomRFA")

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Bayesian inference

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Bayesian inference

Prior $p(\boldsymbol{\theta})$: the strength of our belief in θ without the data Y

Posterior $p(\boldsymbol{\theta}|\boldsymbol{Y})$: the strength of our belief in θ when the data Y are taken into account

Likelihood $p(\boldsymbol{Y}|\boldsymbol{\theta})$: the probability that the data Y could have been generated by the model with parameter values θ

Evidence p(Y): the probability of the data according to the model, determined by summing across all possible parameter values weighted by the strength of belief in those parameter values

→ typically unknown, can be ignored with proportionality

→ essentially a normalizing constant

→ does not enter into determining relative probabilities (models)

Available R packages for Bayesian inference:
library("rstan")
library("spBayes")

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Bayesian inference

Bayes' Rule in a modeling framework:

$$p(\theta|\boldsymbol{Y}) = \frac{p(\boldsymbol{Y}|\theta)p(\theta)}{p(\boldsymbol{Y})} \propto p(\boldsymbol{Y}|\theta)p(\theta)$$

e.g., $\boldsymbol{Y} = (y_1, y_2, \dots, y_n); \theta = (\mu, \sigma, \xi)$

Define *prior distributions* for model parameters θ (a priori knowledge)

Can consider numerous likelihood functions (e.g., *GEV*, GNO, GLO, etc.)

Monte Carlo, acceptance criteria, builds *posterior distributions* of θ

Bayesian inference derives the *posterior probability* as a consequence of a *prior probability* and a *likelihood function*

Available R packages for Bayesian inference:
library("rstan")
library("spBayes")

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Regional Bayesian

Scale annual maxima by at-site mean

Assume scaled maxima within HR described by a single theoretical distribution

Generalized Extreme Value (GEV) distribution

Posterior distributions of $\theta = (\mu, \sigma, \xi)$

→ Quantification of one source of epistemic uncertainty

Available R packages for Bayesian inference:
library("rstan")
library("spBayes")

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Datasets

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Historical Observations

Global Historical Climatology Network:

Integrated database of daily climate summaries from land surface stations (100,000+) across the globe

Includes observations from multiple sources that have been subjected to a the same fully-automated quality control process (Durre et al. 2010)

- Duplication of records
- Exceedance of physical, absolute, climatological limits
- Temporal persistence
- Inconsistencies with neighboring observations

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Historical Observations

Global Historical Climatology Network:

Integrated database of daily climate summaries from land surface stations (100,000+) across the globe

Includes observations from multiple sources that have been subjected to a the same fully-automated quality control process (Durre et al. 2010)

- Duplication of records
- Exceedance of physical, absolute, climatological limits
- Temporal persistence
- Inconsistencies with neighboring observations

Question:

How do we obtain PF estimates at ungauged locations?

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Newman et al. (2015)

Gridded observation-based ensemble dataset of daily precipitation and temperature from 1980 to 2012

Ensemble generation:

*Locally-weighted regression models are used to produce "best estimate" values of precipitation and temperature at 1/8° lat×lon grid

* Regression residuals are used to perturb the best-estimate values with correlated random samples

Resulting dataset:

*100 plausible precipitation and temperature grids

*Each valid over same period

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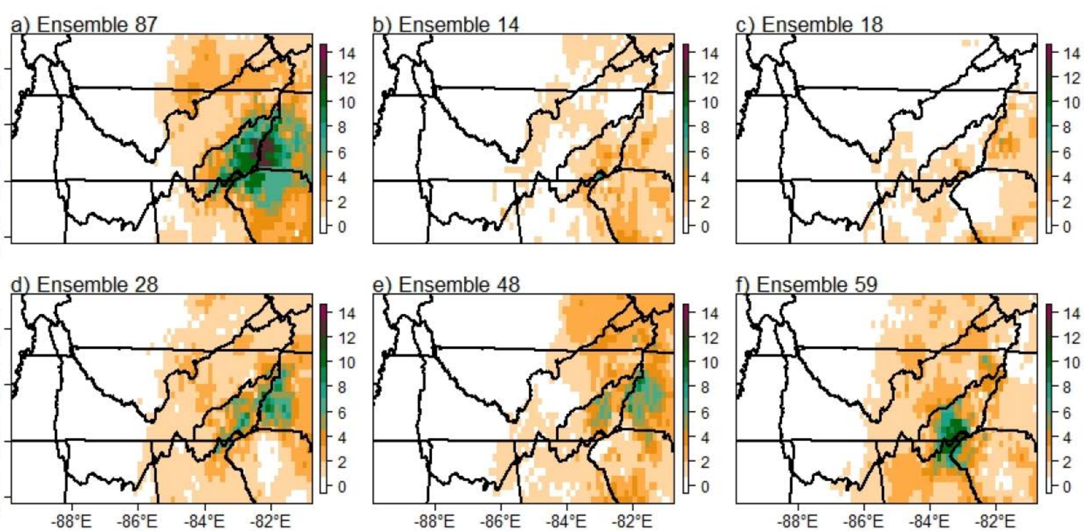
Newman et al. (2015)

Daily precipitation (inches) on September 15, 2004



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Case Study

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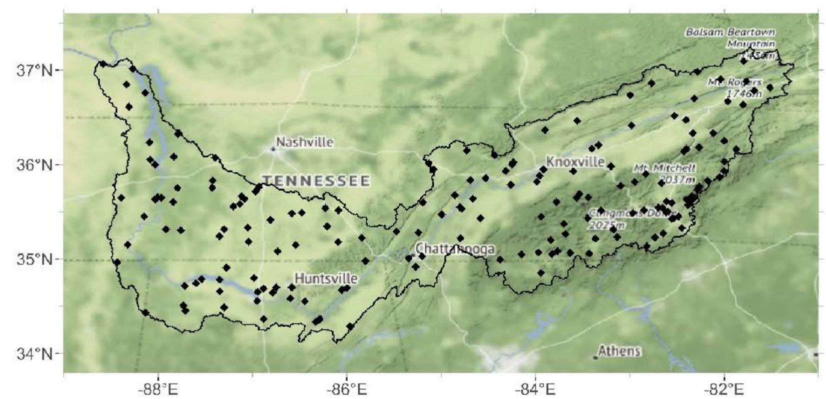
Study Region

Tennessee River Valley watershed



GHCN-Daily gauges with 85% data availability for 10+ years period of record (POR)

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Homogeneous Regions

Methods to define HR (Hosking and Wallis 1997)

- Subjective methods
  - Geographical location
  - Seasonal timing of peak events
  - Mean annual precipitation (MAP)
  - Similar forcing mechanisms (synoptics)
- Objective methods
  - Self-Organizing Maps (SOM)
  - Hierarchical clustering analysis (HCA)
  - Principle component analysis (PCA)
  - Heterogeneity measure

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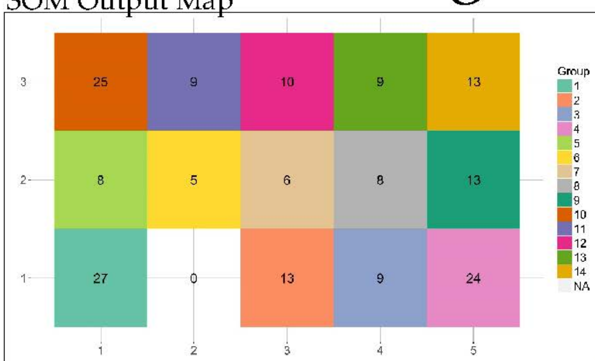
Self-Organizing Map

SOM Output Map



Clustering algorithm used to "group" stations with similar attributes

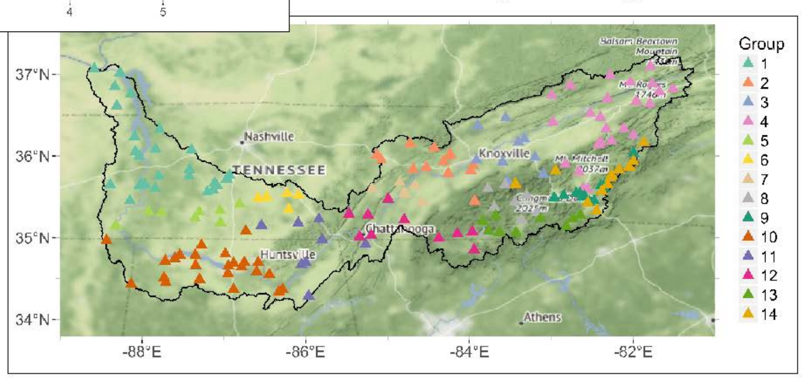
Apply SOM algorithm to :

- Latitude
- Longitude
- Elevation
- *Avg annual precipitation*
- *Avg annual max one-day precipitation*

Each station maps to a single SOM node

Gauges mapped to same node define homogeneous regions

Homogeneous regions need not be contiguous



Available R packages for SOM analysis:
library("som")
library("kohonen")

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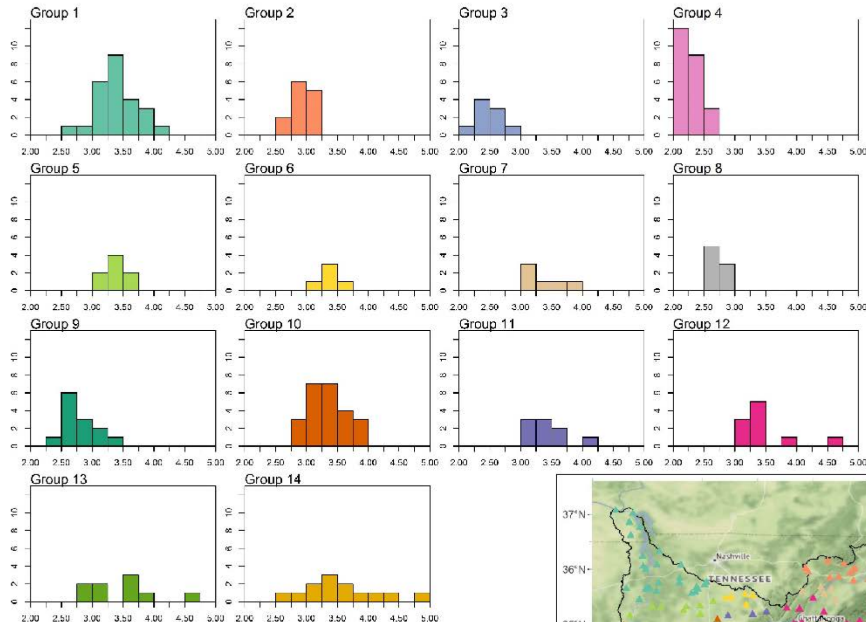
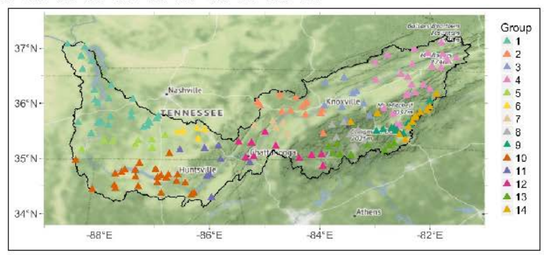
SOM Results – At-Site Means





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L-Moments

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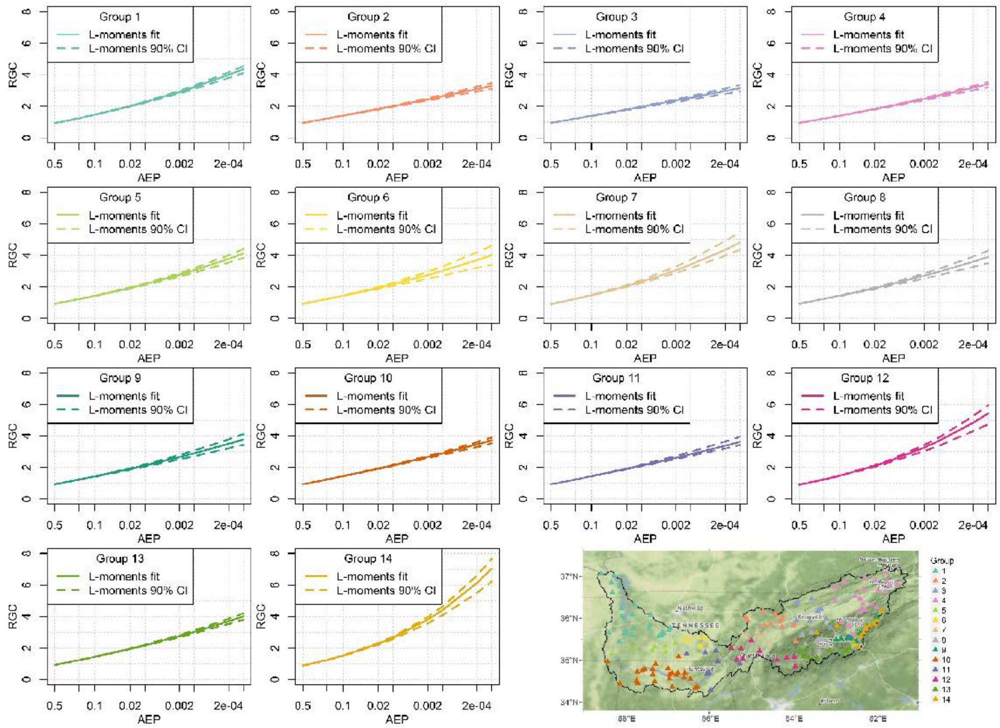
L-Moments RGCs



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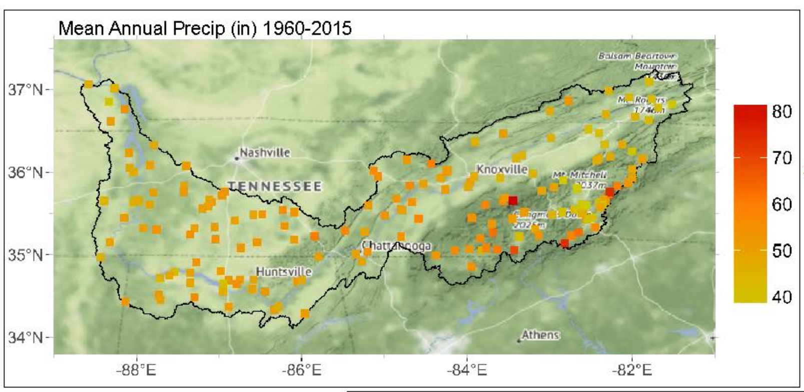
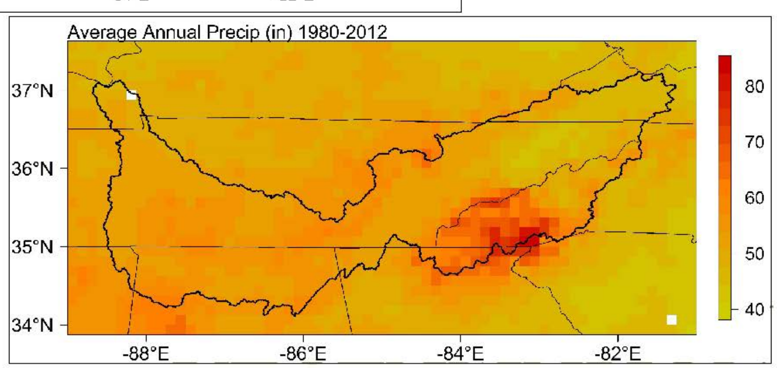
Data Availability



GHCN-Daily dataset

Newman et al. (2015) gridded ensemble



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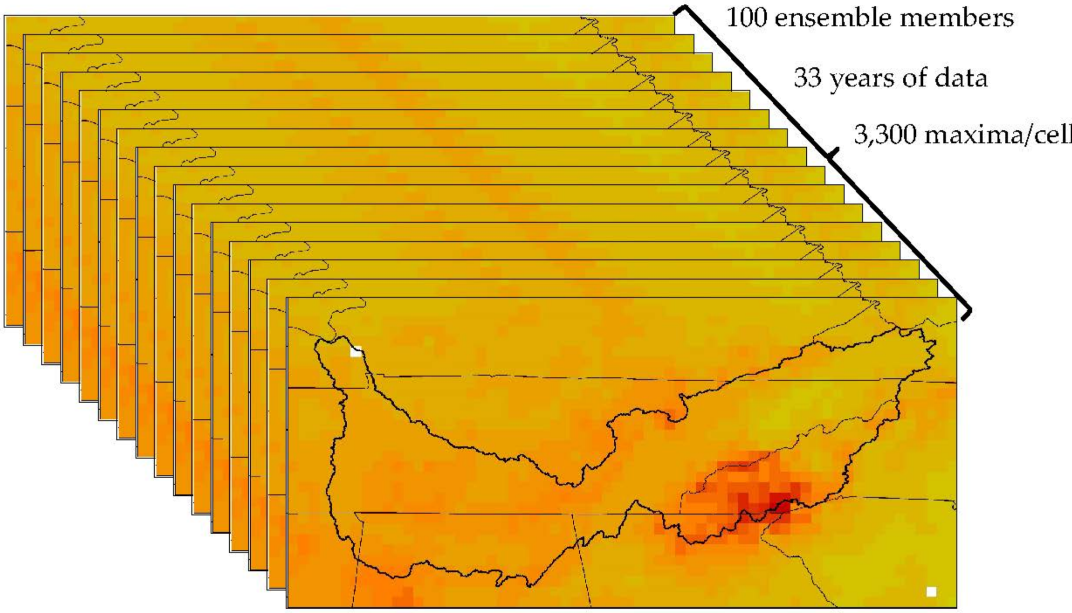
Combined Ensemble



Newman et al. (2015)

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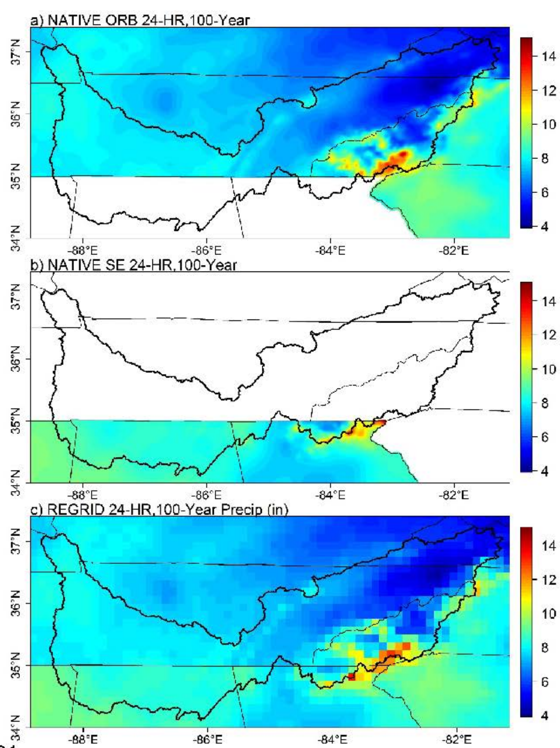
NOAA Atlas 14



Data from Ohio River Basin and Southeast domains use different lat/long grids

Regrid each field to the Newman resolution and then combine fields to produce a single field

In order to compare with Newman estimates, applied two <u>scale factors</u>

- Duration correction
- Areal-reduction factor

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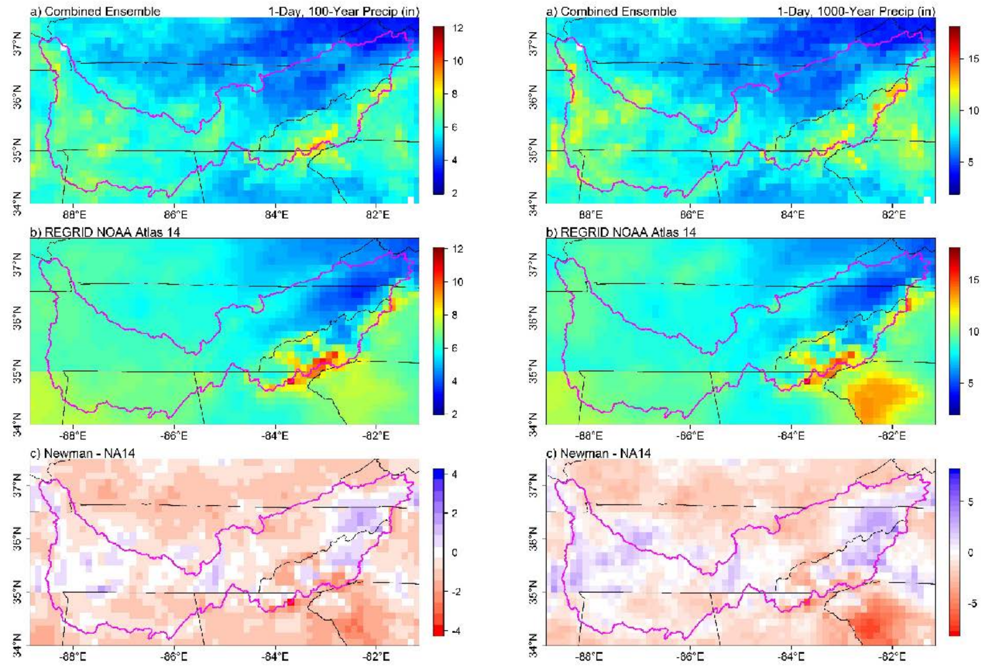
Gridded L-moments



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Bayesian

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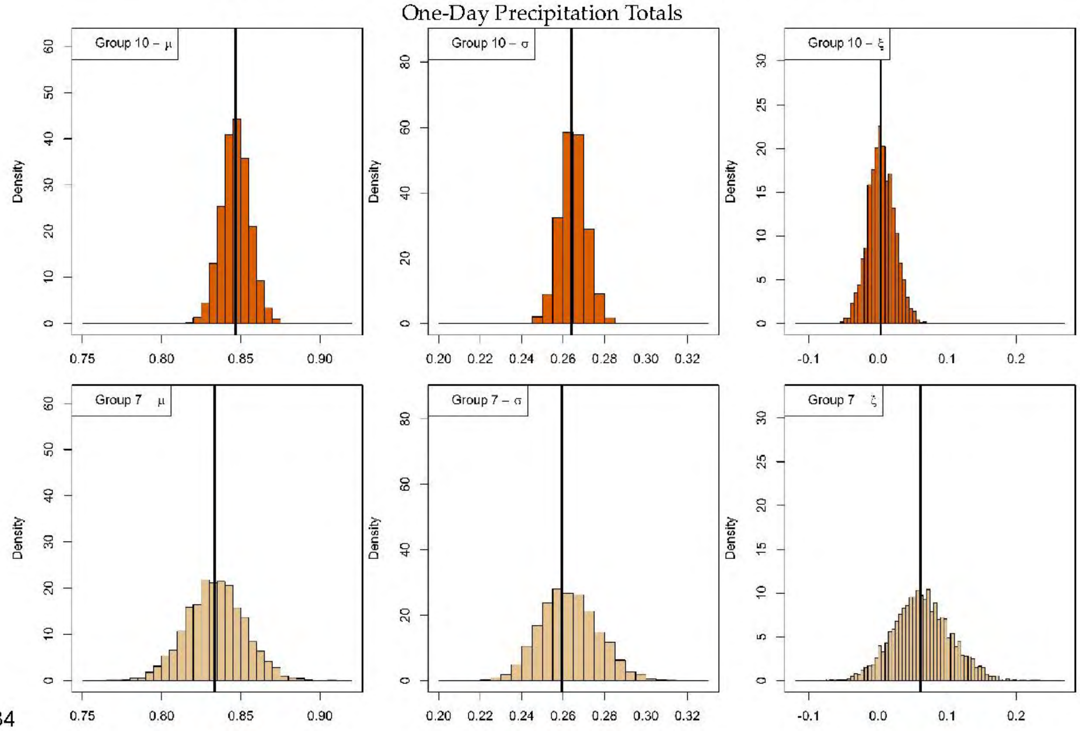
Posterior Distributions

One-Day Precipitation Totals



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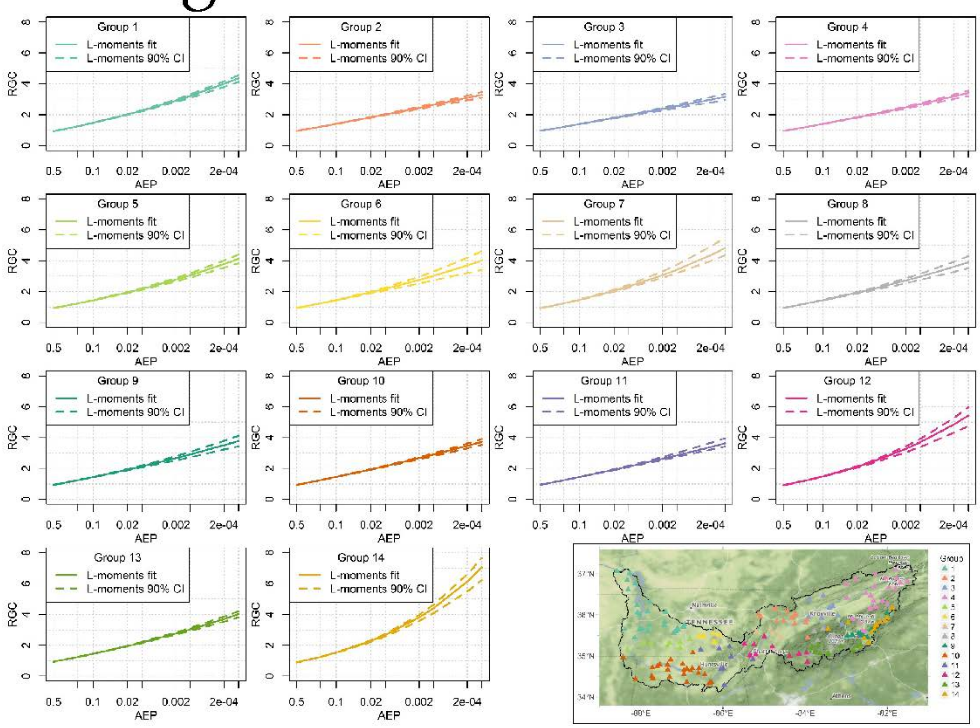
Regional Growth Curves



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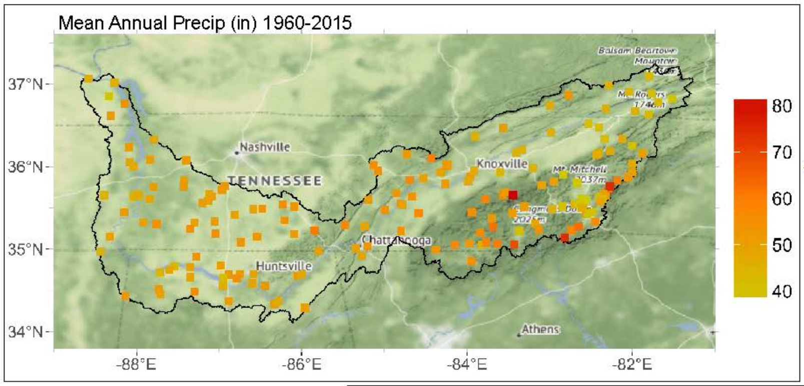
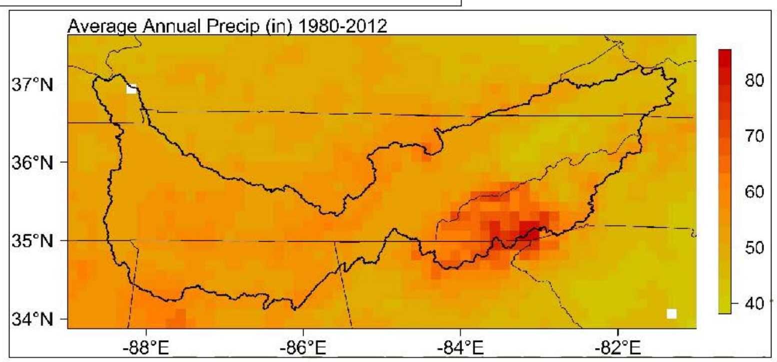
Data Availability



GHCN-Daily dataset

Newman et al. (2015) gridded ensemble



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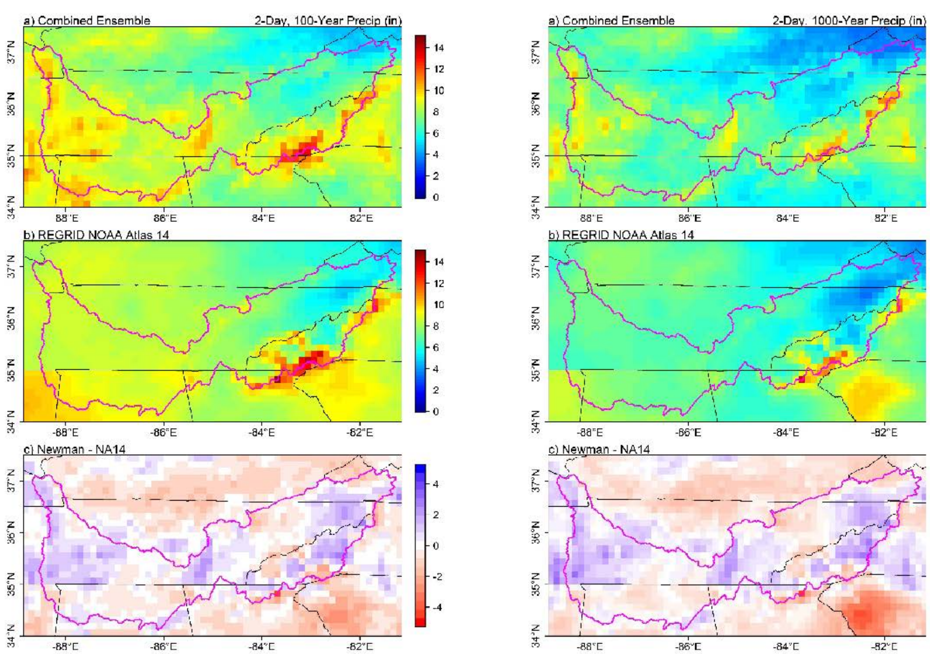
Gridded Bayesian - Medians



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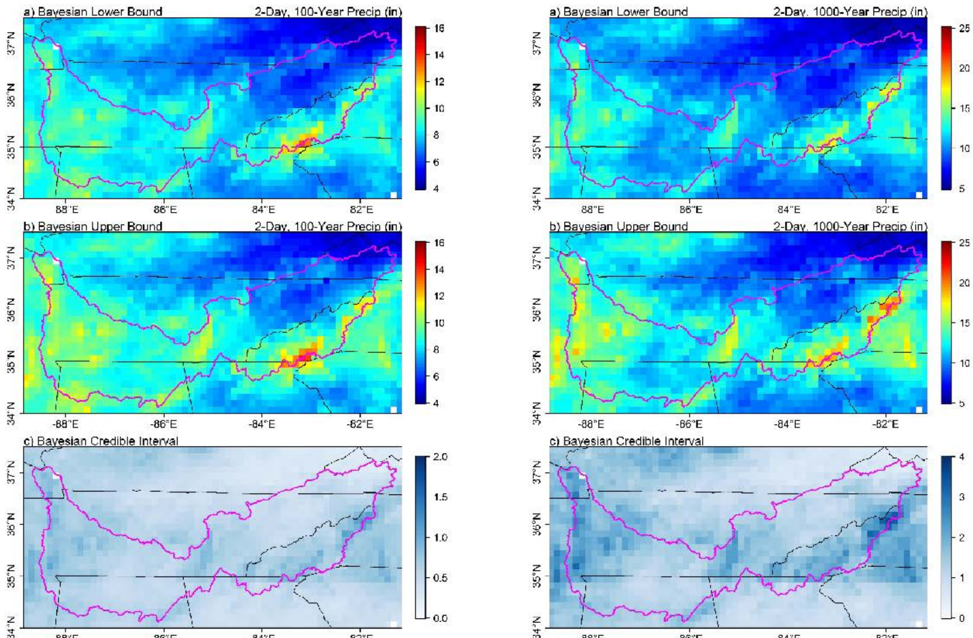
Gridded Bayesian - Uncertainty



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L-Moments vs. Bayesian

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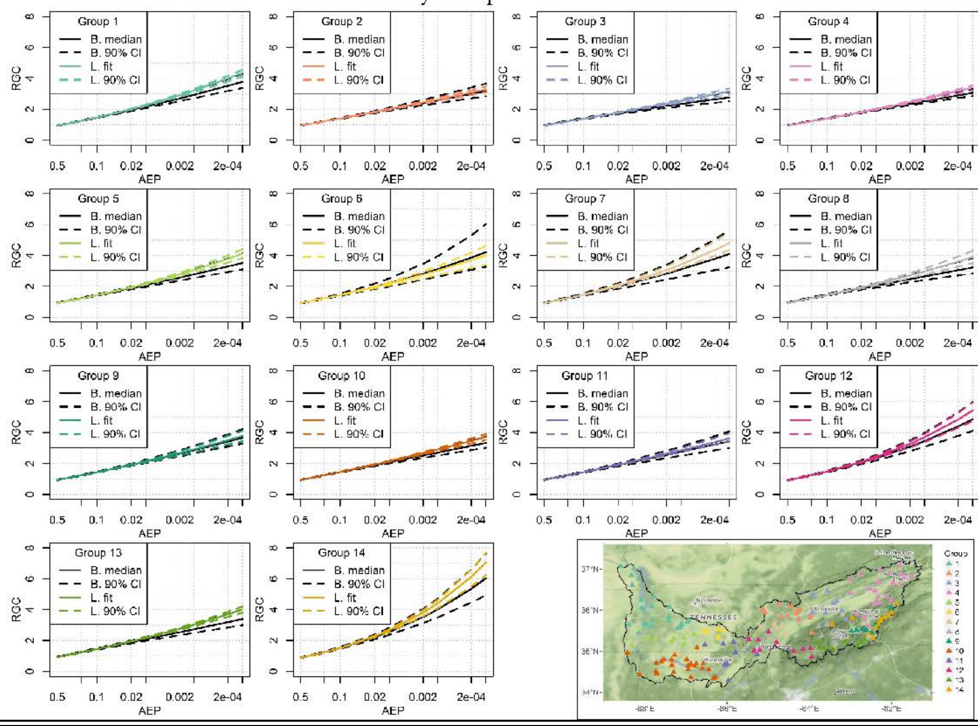
Regional Growth Curves

One-Day Precipitation Totals



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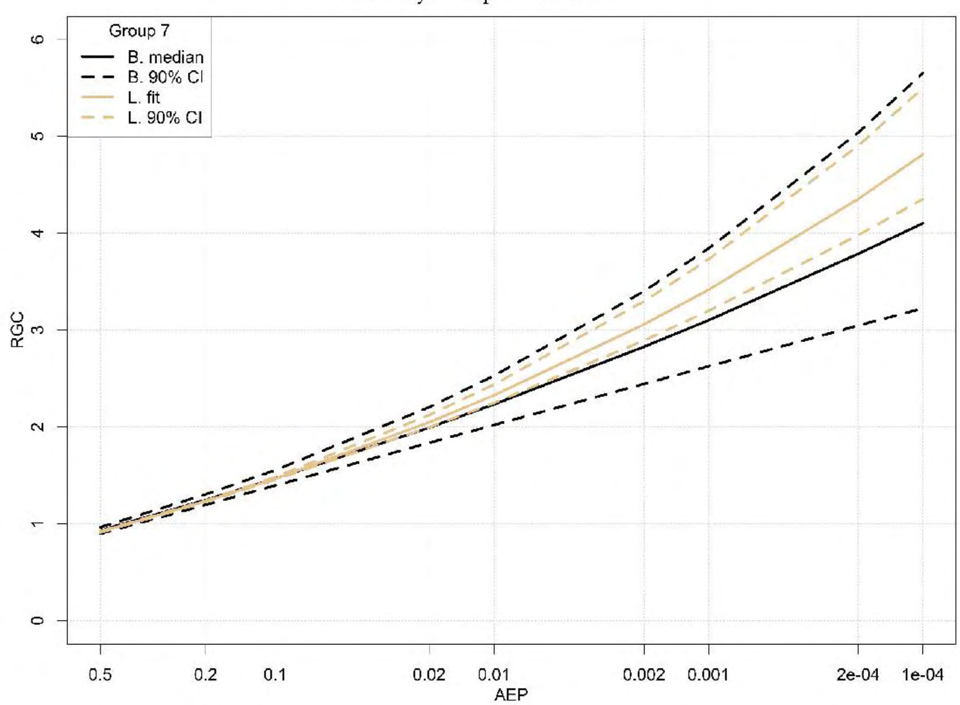
Regional Growth Curves

One-Day Precipitation Totals



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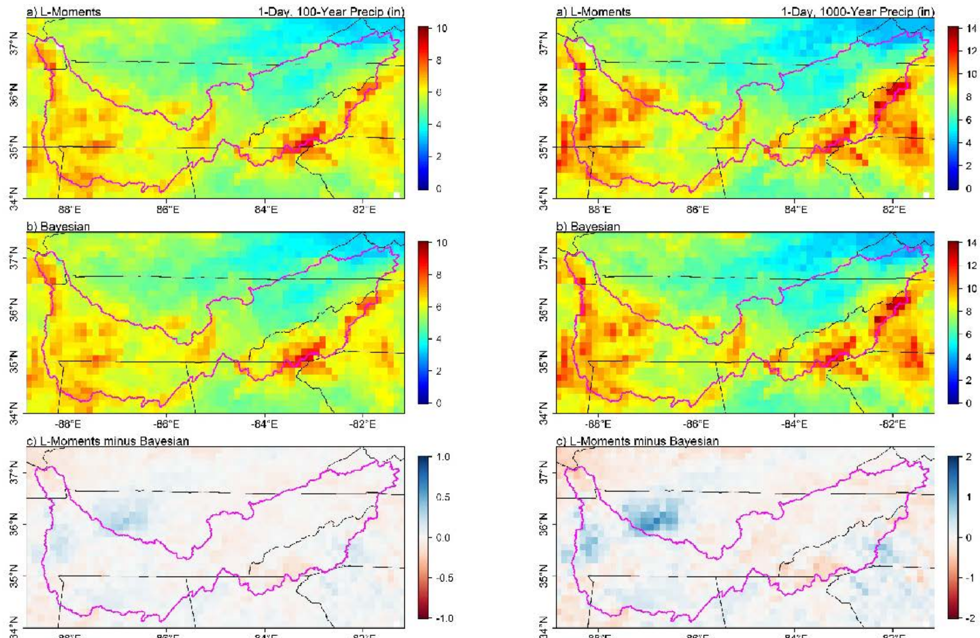
Gridded Frequency Analysis



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Summary

Regional frequency analysis using two methods

- L-moments and Bayesian inference

Homogeneous regions defined using semi-objective clustering algorithm, SOM (Self-Organizing Maps)

- Lon, lat, elev, mean annual precip, mean 1-day maxima
- Effectively accounts for orographics by clustering similar stations

Precipitation-frequency results and uncertainty bounds vary by method

- L-moments uses drop-10% bootstrap resampling
- Bayesian uses Monte Carlo, prior knowledge, likelihood function, acceptance criteria to build *posterior distributions*

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Summary

Regional frequency estimation methods possible on any gridded dataset

- Newman used to address aleatory variability

L-moments and Bayesian produce similar estimates

- Bayesian median and L-moments fit show good agreement (< +/- 2" at 1,000-year return period)
- L-moments uncertainty estimation method lacking for large datasets (3,300 data points, drop-10% bootstrapping)
- Bayesian uncertainty also likely underestimated due to correlated data

Future work could entail multi-model combination

- Better quantify epistemic uncertainty via numerous gridded datasets, station-based datasets

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Questions?

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3.3.2.3.3 Questions and Answers

None.

3.3.3 Day 1: Session 1C - Storm Surge

Session Chair: Joseph Kanney, NRC/RES/DRA/FXHAB

Development of guidance for application of improved mechanistic and probabilistic modeling techniques for key flood generating processes and flooding scenarios.

3.3.3.1 Quantification of Uncertainty in Probabilistic Storm Surge Models Norberto C. Nadal-Caraballo , Ph.D. and Victor Gonzalez*, P.E., U.S. Army Engineer R&D Center, Coastal and Hydraulics Laboratory (Session 1C-1; ADAMS Accession No. ML17355A088)

3.3.3.1.1 Abstract

Probabilistic flood hazard assessment (PFHA) of critical infrastructure located in coastal zones requires the characterization of the storm surge hazard and associated uncertainty. The joint probability method with optimal sampling (JPM-OS) has become the standard probabilistic model used to assess coastal storm hazard in hurricane-prone coastal regions of the United States. Other methods such as global climate modeling (GCM) downscaling and Monte Carlo Simulation methods have also been applied. The U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory (ERDC) is performing a comprehensive assessment of uncertainties in probabilistic storm surge models in support of the NRC efforts to develop a framework for probabilistic storm surge hazard assessment for nuclear power plants. The treatment of uncertainties in the JPMX-OS methodology varies by study and is typically limited to the quantification and inclusion of uncertainty as an error term in the JPM integral. Traditionally, these errors have been regarded as epistemic uncertainties because, theoretically, they could be reduced by collecting additional data, refining the numerical models, and constructing more efficient synthetic storm suites. In practice, past individual studies, for example, have been based on a defined set of data sources and have employed a single approach for estimating each of the JPM components (e.g., computation of SRR, univariate distributions, distribution discretization method, development of synthetic storm suites, others), limiting the understanding of the range of uncertainty.

The treatment of uncertainties in the present study is based on USNRC guidance on probabilistic seismic hazard assessment (PSHA). In this paradigm, the epistemic uncertainty arises from the selection and application of technically defensible alternative data, methods, and models at each step of the probabilistic storm surge modeling. Once the epistemic uncertainty is quantified, it is propagated through the use of logic trees. This allows for the computation of a family of hazard curves, with individual curves representing each of the alternate modeling approaches. In order to quantify the epistemic uncertainty associated with probabilistic storm surge models, this study evaluated data sources and methods associated with the different applications of the JPM-OS, GCM, and MCS approaches, and determined the data and methods that should be carried forward. Specific topics that were assessed include storm recurrence rate models, methods for defining joint probability of storm parameters, methods for generating synthetic storm simulation sets, integration methods, and integration of aleatory variability. The analysis of the logic tree branches representing the center, body, and range of the data and methods employed by each probabilistic storm surge model (e.g., JPM-OS, GCM, and MCS) yielded a family of hazard curves. To convey the range of the epistemic uncertainty, a statistical analysis was performed to compute fractile storm hazard curves (equivalent to non-exceedance confidence limits) including the mean, 0.05, 0.16, 0.5 (median), 0.84, and 0.95.

3.3.3.1.2 Presentation

3rd Annual Probabilistic Flood Hazard Assessment Workshop
Rockville, MD – December 4-5, 2017

ERDC
Engineer Research and Development Center

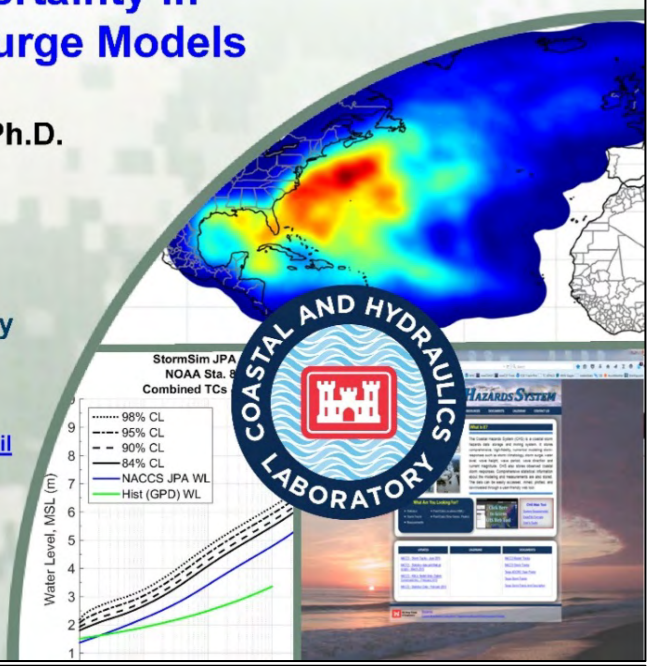
Quantification of Uncertainty in Probabilistic Storm Surge Models

Norberto C. Nadal-Caraballo, Ph.D.

Team: **Victor Gonzalez, P.E.**
Amanda B. Lewis
Efrain Ramos-Santiago

Coastal and Hydraulics Laboratory
US Army Engineer R&D Center

Norberto.C.Nadal-Caraballo@usace.army.mil



U.S. ARMY
US Army Corps of Engineers

Outline

- Introduction
  - Objectives and treatment of uncertainty
  - Project tasks
  - Logic tree approach
- Storm Recurrence Rate models
- Marginal (univariate) Distributions
- Generating Synthetic Storm Sets
- Characterization & Propagation of Uncertainty

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Introduction

- Study objectives:
  - Identification of technically defensible data sources, models, and methods for the computation of storm surge.
  - Assessment for carrying forward for evaluation of epistemic uncertainty.
- Treatment of uncertainty in present study:
  - Follows probabilistic seismic hazard analysis (PSHA).
  - Epistemic uncertainty is quantified and propagated through logic tree approach.
  - Differences between a numerical model and the natural phenomenon is prevalent (error term) → **aleatory**
  - Reduction of uncertainty in the selection and application of alternative data, methods, and models → **epistemic**

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Project Overview (Tasks)

- Task 1 Literature Review
- Task 2 Storm Recurrence Rate Models
- Task 3 Defining Joint Probability of Storm Parameters
- Task 4 Generating Synthetic Storm Simulation Sets
- Task 5 Probabilistic Modeling of Numerical Surge Simulation Errors
- Task 6 Synthesis and Final Report Preparation
- Task 7 Transfer of Knowledge

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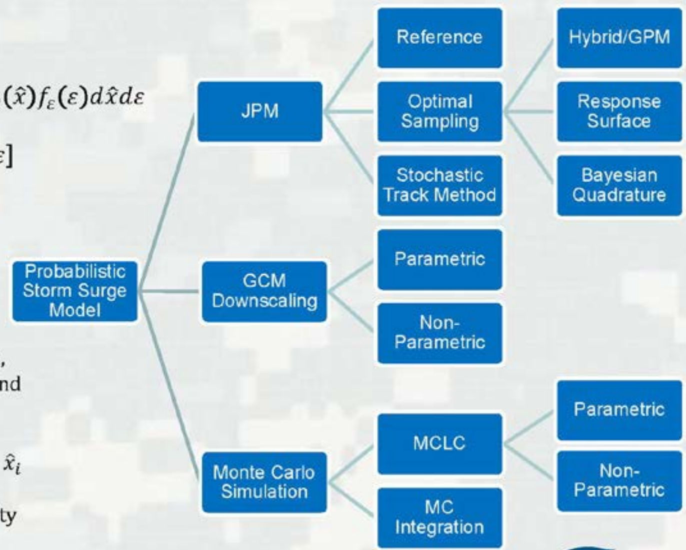
Logic Tree Approach

JPM Integral

$$\lambda_{r(\hat{x})>r} = \lambda \int P[r(\hat{x}) + \varepsilon > r|\hat{x},\varepsilon]\, f_{\hat{x}}(\hat{x}) f_{\varepsilon}(\varepsilon) d\hat{x} d\varepsilon$$

$$\approx \sum_i^n \lambda_i\, P[r(\hat{x}) + \varepsilon > r|\hat{x},\varepsilon]$$

where:
$\lambda_{r(\hat{x})>r}$ = AEP of TC response r due to forcing vector $\hat{x}$
$\hat{x} = f(x_o, \theta, \Delta p, R_{max}, V_t)$
λ = SRR (storms/yr/km)
$\hat{\lambda}_i$ = probability mass (storms/yr) or λp_i, with p_i=product of discrete probability and TC track spacing (km)
$P[r(\hat{x}) + \varepsilon > r|\hat{x},\varepsilon]$ conditional probability that storm i with parameters $\hat{x}_i$ generates a response larger than r
ε = unbiased error or aleatory uncertainty of r



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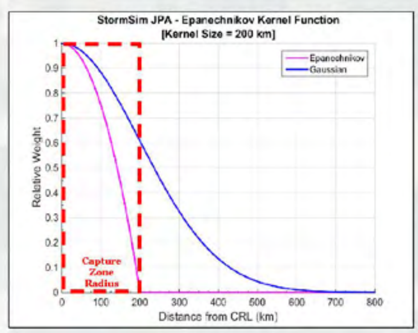
Task 2: Epistemic Uncertainty in SRR Models

- Data sources and methods used for the computation of site-specific storm recurrence rate (SRR) models.
- Models for Calculating SRR
  - Uniform kernel function (UKF) or capture zone
  - Gaussian kernel function (GKF)
  - Epanechnikov kernel function (EKF)
- Topics
  - Investigate SRR aleatory uncertainty.
  - Compare Models for Estimation of SRR & Impact on Hazard Curves.



$$\lambda = \frac{1}{T}\sum_i^n w(d_i)$$

$$w(d_i) = \frac{1}{h_d}\begin{cases}0.5, & if \left|\frac{d_i}{h_d}\right| < 1\\ 0, & otherwise\end{cases}$$

UKF

$$w(d_i) = \frac{1}{\sqrt{2\pi}h_d} exp\left[-\frac{1}{2}\left(\frac{d_i}{h_d}\right)^2\right]$$

GKF

$$w(d_i) = \frac{1}{h_d}\begin{cases}\frac{3}{4}\left[1-\left(\frac{d_i}{h_d}\right)^2\right], & if \left|\frac{d_i}{h_d}\right| < 1\\ 0, & otherwise\end{cases}$$

EKF

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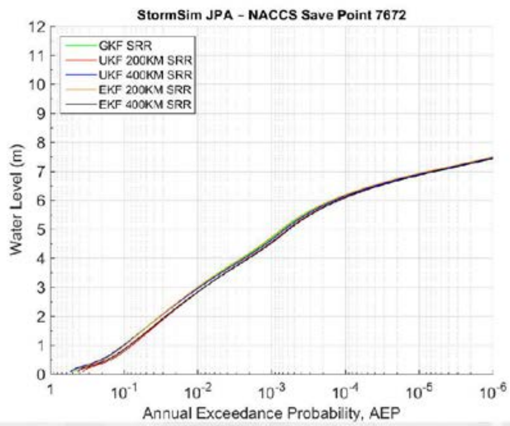
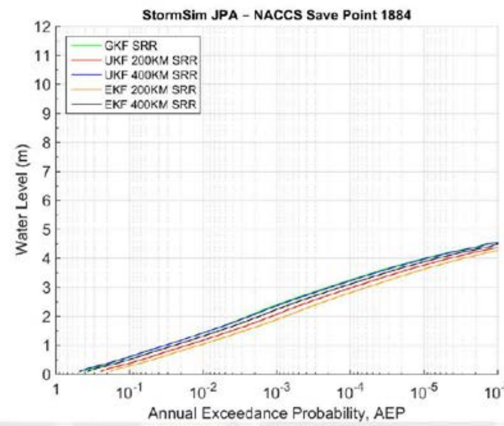
Task 2: Epistemic Uncertainty in SRR Models

- Effect of Kernel functions and sizes on WL hazard curve



The Battery, NY



Boston, MA

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Task 2: Epistemic Uncertainty in SRR Models

- **Findings**
  - The lower SRR uncertainty was associated with locations with higher TC occurrences (sample size).
  - Kernel function introduces small variability in hazard curve.
  - Relative contributions of aleatory uncertainty ($\Delta p \geq 28$ hPa)
    - Sampling uncertainty – 65%
    - Selected period of record – 19%
    - Gaussian kernel size – 15%
    - Observational data – 1%
  - Although resampling uncertainty and observational uncertainty could be classified as aleatory variability, they could also be considered epistemic from the point of view of reducibility.
    - Passage of time → increase sample size
    - Improvement in observation technologies → increase measurement accuracy
    - Discretized and incorporated as branch in logic tree.

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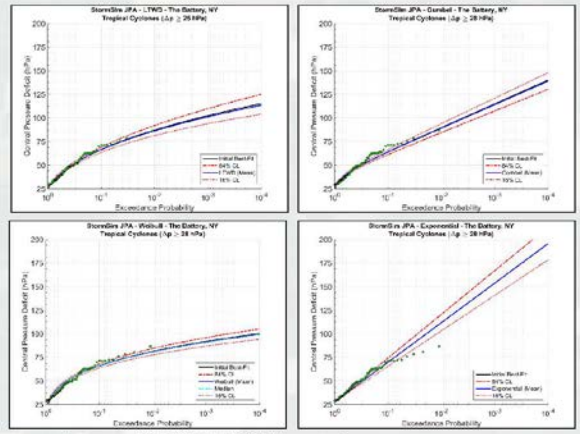
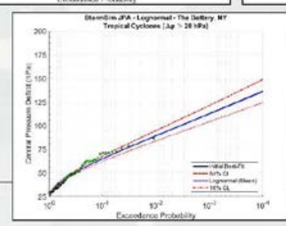
Task 3: Data, Models and Methods for Defining Joint Probability of Storm Parameters

- **Task Description**
  - Identification of technically defensible TC parameter data sources, screening methods, and parameterization schemes for development of probability distribution.
- **Topics:**
  - Selection of probability distributions
  - Evaluate technically defensible data sources





Δp Examples

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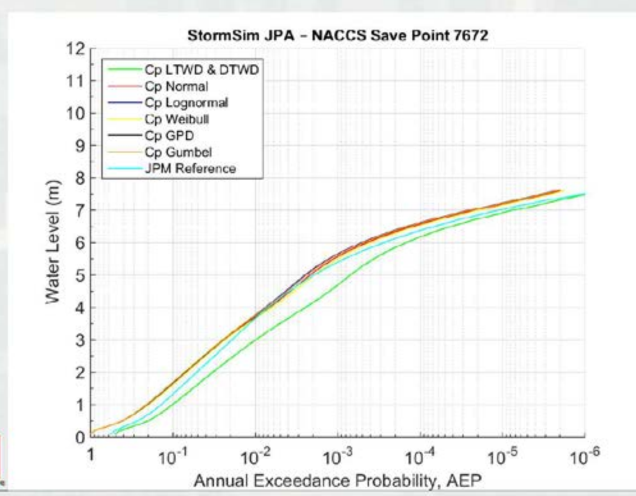
Task 3: Data, Models and Methods for Defining Joint Probability of Storm Parameters

- Effect of selection of Δp distribution on hazard curve



LTWD & DTWD curve considers the discretization of TCs into high and low intensity.

The effect is to lower the hazard curve.

Choice of Δp distribution showed limited impact

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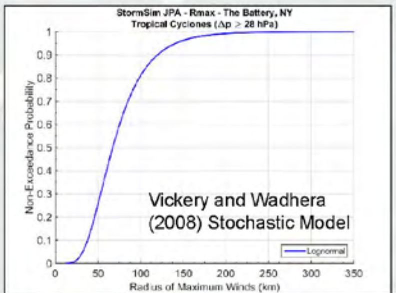
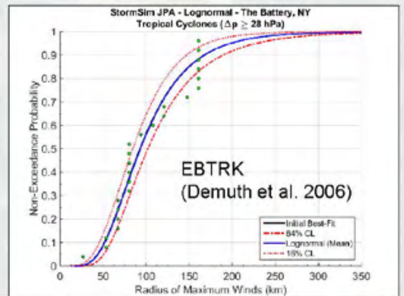
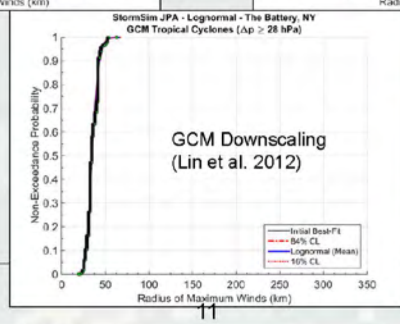
Task 3: Data, Models and Methods for Defining Joint Probability of Storm Parameters

- Comparison of R_{max} probability distributions





Similar curves resulting from the Vickery model and EBTRK reanalysis.



GCM plot suggests that extratropical transition of TCs is not being adequately represented.

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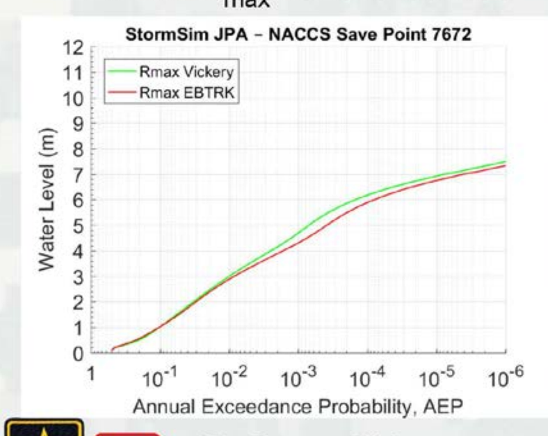
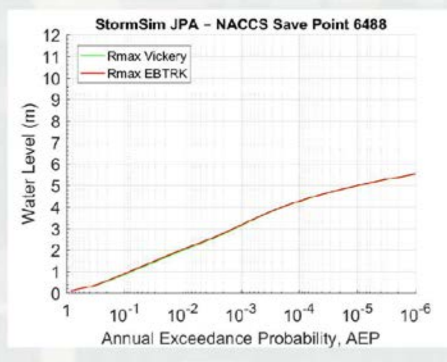
Task 3: Data, Models and Methods for Defining Joint Probability of Storm Parameters

- Vickery and Wadhera and EBTRK R_{max} hazard curves



The Battery, NY



Virginia Beach, VA

Small variation in hazard curves for EBTRK and Vickery and Wadhera (2008) stochastic model → **both lognormal.**

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Task 3: Data, Models and Methods for Defining Joint Probability of Storm Parameters

- **General Findings**
  - The most relevant factor in choosing distribution type was how well it described the low-frequency tails.
  - More than one statistical distribution could be valid for a given TC parameter.
  - Comparison of viable fits usually did not reveal significant differences. Limited effect confirmed by hazard curve comparisons.
  - The sampling technique used for the generation of synthetic TCs may lessen the significance of selecting a given probability distribution for large discretization intervals.
  - The judgment of carry forward a given dataset, method, or model was found to be highly dependent on the location.

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Task 4: Data, Models, and Methods for Generating Synthetic Storm Simulation Sets

- Task Description
  - Capture full range of technically defensible data and methods for generating synthetic storm sets required to fully characterize and propagate uncertainties in storm surge estimates.
  - Methods tested for generating synthetic storm simulation sets
    - JPM Reference – 74,430 TCs
    - JPM-OS – 1,050 TCs
    - Monte Carlo Simulation: Life Cycle – 211,997 TCs & Integration – 211,997 TCs
    - CGM Downscaling – 1,470 TCs
    - Methods for calculating probability mass that explicitly consider parameter correlations – 211,997 TCs
      - Multivariate Gaussian Distribution
      - Multivariate Gaussian Copula
      - Multivariate Student's t Copula

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Task 4: Data, Models, and Methods for Generating Synthetic Storm Simulation Sets

- **Reference Set**
  - Traditional JPM approach → All parameter combinations →Large set of storms (74,430 TCs)
  - A Gaussian process metamodel (GPM) (Jia et al. 2016) was used to develop tens of hundreds of TCs.
    - The GPM is conceptually similar to response surface.
      - initial discretization of the joint probability distribution is refined by regression or interpolation of storm surge from additional TC parameter combinations.
    - The GPM used in this study was trained using the 1050 synthetic TCs developed as part of the NACCS (Nadal-Caraballo et al. 2015).

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Task 4: Data, Models, and Methods for Generating Synthetic Storm Simulation Sets

- **Monte Carlo Simulation**
  - **Monte Carlo Life-Cycle**
    - Univariate distributions of TC parameters were sampled for a 1,000,000-yr period, which resulted in 200,000+ TCs.
    - **No probability masses** required.
      - TC's sampled based on their likelihood of occurrence and joint p. Storm surge hazard curve from **empirical distribution** (Weibull plotting position).
    - Mean hazard curve and confidence levels calculated through bootstrap resampling using replicated storm surge values with added discretized uncertainty.
  - **Monte Carlo Integration (MCI)** (Wyncoll and Gouldby 2015)
    - Probabilities are calculated as the percent of TCs with response greater than a set of surge elevation bins. **No probability masses** required.
    - $P(C > c) \approx \frac{L_c}{L} * \lambda$, where L_c is the number of Monte Carlo realizations that exceed c, L is the total number of Mote Carlo realizations, and λ is the sample intensity (storms/yr).

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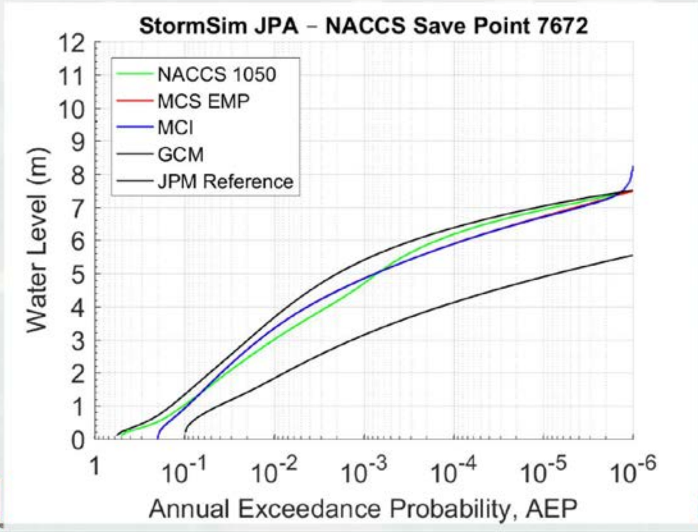
Task 4: Data, Models, and Methods for Generating Synthetic Storm Simulation Sets

- **GCM Downscaling** (Lin et. al 2012)
  - Storm surges determined by GCM-driven statistical/deterministic hurricane model with hydrodynamic surge models.
  - Synthetic TCs tracks are generated according to large-scale atmospheric and ocean environments rather than historical TCs.
  - 1,470 tracks covering a time period from 1970-2010.
  - The storm surge responses were simulated by applying GCM parameters and tracks to the previously trained GPM
  - Stochastic simulation technique (SST) consisting of combined empirical and GPD fits was applied to the storm surge values to obtain hazard curve.

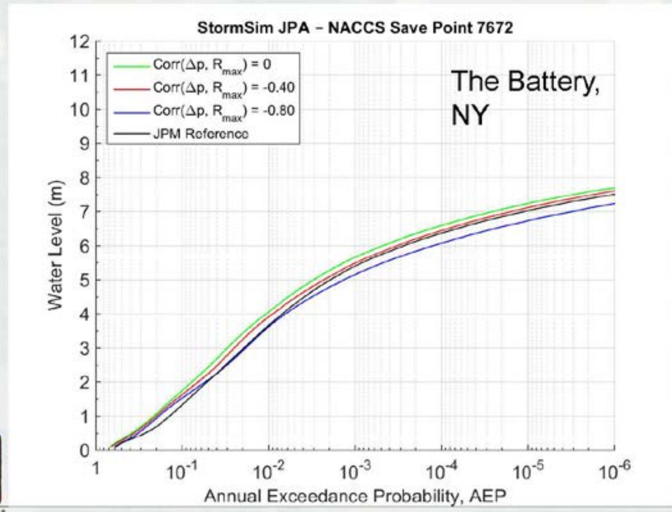
Task 4: Data, Models, and Methods for Generating Synthetic Storm Simulation Sets

- **Methods hazard curves comparison**



Task 4: Data, Models, and Methods for Generating Synthetic Storm Simulation Sets

- MVGC: correlation between Δp and R_{max}



The two are negatively correlated

Independence between the two parameters results in more combinations of high intensity and large radius → larger surge

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Task 5: Approaches for Probabilistic Modeling of Numerical Surge Simulation Errors

- **Task Description**
  - Investigate approaches for characterizing and modeling errors within the probabilistic framework constituted by modeling of storm surge.
  - Topics:
    - Comparison of approaches for the characterization of uncertainty
      - Constant uncertainty (e.g. 0.61m)
      - Proportional uncertainty (e.g. 20%)
      - Combined constant and proportional uncertainty [e.g., min(20%, 0.61m)]
    - The significance of different number of discrete values (or random samples) from the Gaussian distribution will be evaluated by comparing results using 30, 100, 300,1000, and 3000 values.

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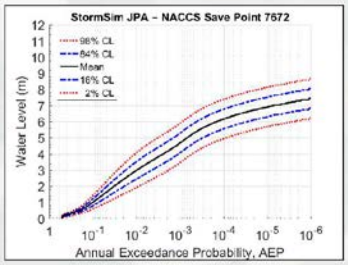
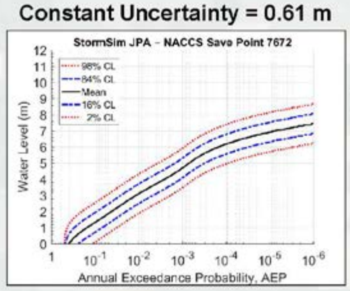
Task 5: Approaches for Probabilistic Modeling of Numerical Surge Simulation Errors

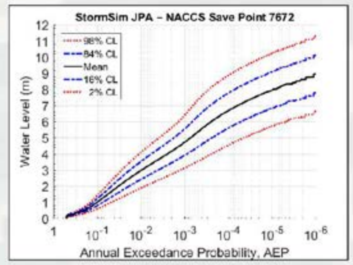
- **Results – Characterization of Uncertainty**



Uncertainty = min(20%, 0.61m)

Constant Uncertainty = 0.61 m





Proportional Uncertainty = 20%

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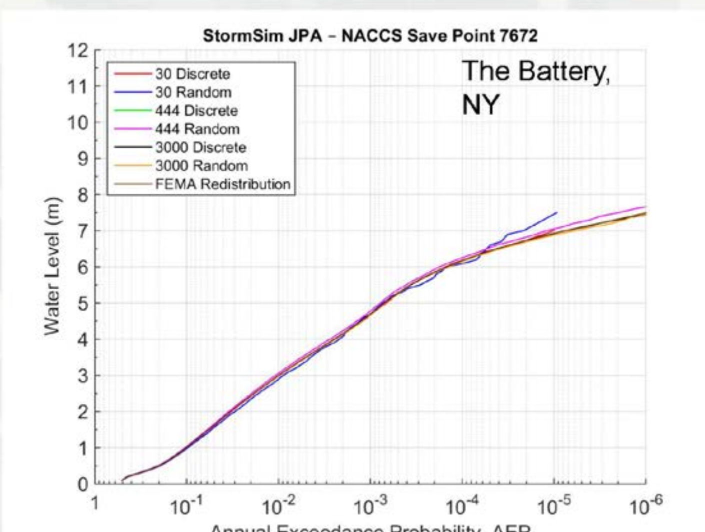
Task 5: Approaches for Probabilistic Modeling of Numerical Surge Simulation Errors

- Incorporating uncertainty in the integration



$WL \rightarrow WL_1, WL_2 \ldots WL_n$

n = number of times WL is replicated and normal distribution discretized or number of times it is sampled.

$$WL_n = \mu + \sigma(Z^*)$$

Z^*=

Discrete $(Z_1 \ldots Z_n)$

Randomly sampled $(Z_1 \ldots Z_n)$

Random sampling increases hazard curve tail for 30 and 444 partitions.

FEMA redistribution and 444 partitions were equivalent

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Task 6: Synthesis

- **Task Description**
  - ► Develop approach to characterize, quantify, and propagate both aleatory and epistemic uncertainties through the probabilistic framework of storm surge assessment process in order to develop robust flood hazard curves for use in NPPs applications.
  - ► Topics:
    - Treatment of uncertainty (Logic trees)

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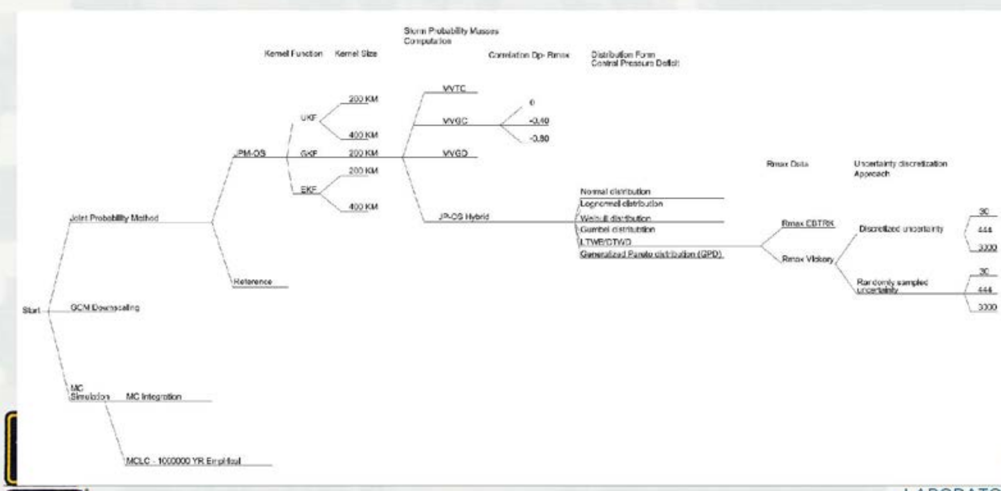
Task 6: Synthesis

- Preliminary example: Surge hazard logic tree



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Task 6: Synthesis

- Logic tree table and weight assignment

Number	Description	Step 1	Step 2 JPM method	Step 3 kernel function	Step 4 kernel size	Step 5 ProbMass	Step 6 Corr	Step 7 Distribution	Step 8 Rmax	Step 9 Discretization	Step 10 # Discretizations	Weight
1	JPM-OS UKF 200km JPM-OS Hybrid LTWD/DTWD Rmax Vickery Discretized 444			0.1	0.75	-	-	-	-	-	-	0.042
2	JPM-OS UKF 400km JPM-OS Hybrid LTWD/DTWD Rmax Vickery Discretized 444				0.25	-	-	-	-	-	-	0.014
3	JPM-OS EGF 200 km JPM-OS Hybrid LTWD/DTWD Rmax Vickery Discretized 444			0.1	0.75	-	-	-	-	-	-	0.047
4	JPM-OS EGF 400 km JPM-OS Hybrid LTWD/DTWD Rmax Vickery Discretized 444				0.25	-	-	-	-	-	-	0.014
5	JPM OS GKF 200 km MVTC					0.025						0.011
6	JPM-OS GKF 200 km MVGD				-	0.025	-	-	-	-	-	0.011
7	JPM-OS GKF 200 km MVGC zero corr				-		0.1	-	-	-	-	0.009
8	JPM-OS GKF 200 km MVGC -0.4 corr				-	0.2	0.8	-	-	-	-	0.072
9	JPM-OS GKF 200 km MVGC -0.80 corr				-		0.1	-	-	-	-	0.009
10	JPM-OS GKF 200 km JPM-OS Hybrid Lognormal Cp Rmax Vickery Discretized 444		0.75		-		-	0.1	-	-	-	0.034
11	JPM OS GKF 200 km JPM OS Hybrid Weibull Cp Rmax Vickery Discretized 444	0.75						0.1				0.034
12	JPM-OS GKF 200 km JPM-OS Hybrid Gumbel Cp Rmax Vickery Discretized 444			0.8	-		-	0.15	-	-	-	0.051
13	JPM-OS GKF 200 km JPM-OS Hybrid GPD Cp Rmax Vickery Discretized 444				-		-	0.15	-	-	-	0.051
14	JPM-OS GKF 200 km JPM-OS Hybrid LTWD/DTWD Rmax EBTRK				-		-		0.25	-	-	0.042
15	JPM-OS GKF 200 km JPM-OS Hybrid LTWD/DTWD Rmax Vickery Discretized 30				-	0.75	-				0.05	0.005
16	JPM-OS GKF 200 km JPM-OS Hybrid LTWD/DTWD Rmax Vickery Discretized 444				-		-			0.8	0.7	0.071
17	JPM-OS GKF 200 km JPM-OS Hybrid LTWD/DTWD Rmax Vickery Discretized 3000				-		-	0.5	0.75		0.25	0.025
18	JPM-OS GKF 200 km JPM-OS Hybrid LTWD/DTWD Rmax Vickery Random 30				-		-				0.05	0.001
19	JPM-OS GKF 200 km JPM-OS Hybrid LTWD/DTWD Rmax Vickery Random 444				-		-			0.2	0.7	0.018
20	JPM-OS GKF 200 km JPM-OS Hybrid LTWD/DTWD Rmax Vickery Random 3000				-		-				0.25	0.006
21	JPM Reference		0.25	-	-	-	-	-	-	-	-	0.188
22	GCM	0.05										0.050
23	MCLC	0.2	-	-	-	-	-	-	-	-	-	0.200
	SUM											1.000

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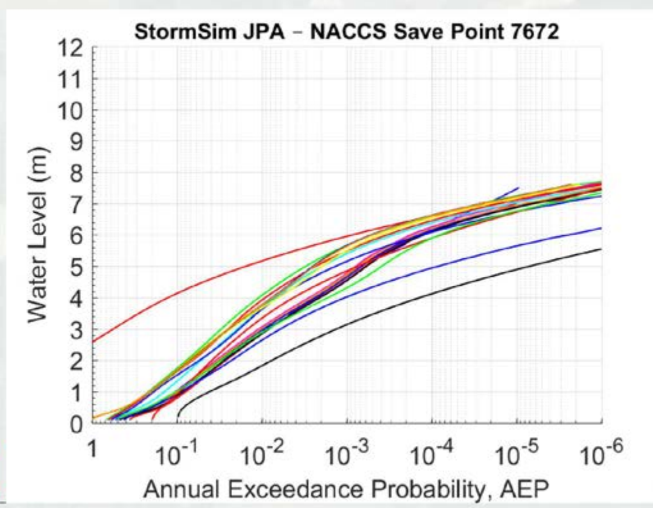
Task 6: Synthesis

- Family of hazard curves



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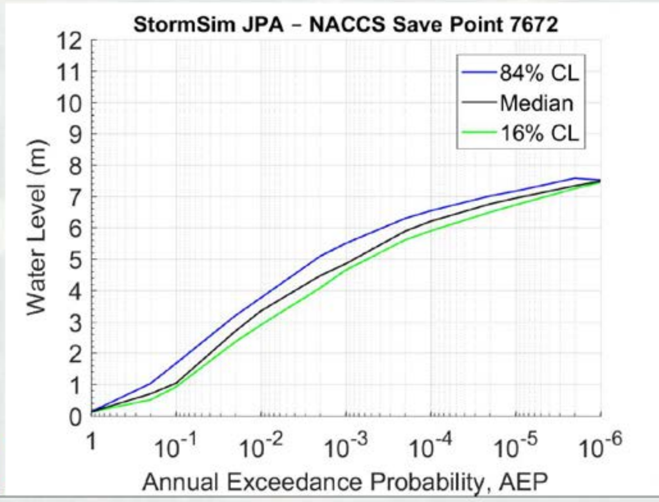
Task 6: Synthesis

- Median hazard curve with confidence limits



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3.3.3.1.3 Questions and Answers

None.

3.3.3.2 Probabilistic Flood Hazard Assessment – Storm Surge John Weglian, EPRI (Session 1C-2; ADAMS Accession No. ML17355A089)

3.3.3.2.1 Abstract

A storm surge is a rise in water level driven by winds from an approaching storm. While this is typically associated with hurricanes, other storm types can also produce a storm surge. EPRI has one research report on estimating the frequency of various magnitudes of storm surge based on an analysis of historical water levels. More research is currently underway to demonstrate how simulations of a hurricane can be used to estimate the frequency of various storm surge levels at a particular location.

3.3.3.2.2 Presentation

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Probabilistic Flood Hazard Assessment

Storm Surge

John E. Weglian
Senior Technical Leader

3rd NRC External Flooding Research Workshop
December 4-5, 2017

EPRI Report on Storm Surge

- EPRI report 3002008111, Probabilistic Flooding Hazard Assessment for Storm Surge with an Example Based on Historical Water Levels
- Provides generic PFHA process as applied to Storm Surge
- Available data and storm type that leads to storm surges for site of interest determines the simulation approach
  - Controlling storm is a hurricane: atmospheric parameters such as central pressure deficit, radius of maximum wind, and maximum wind speed as well as tidal levels can be modeled in the Monte Carlo simulation
  - Controlling storm is not hurricane: historical water levels can be utilized to determine mean sea level or average lake level, storm surge level, and wind-wave effects using Monte Carlo simulation techniques

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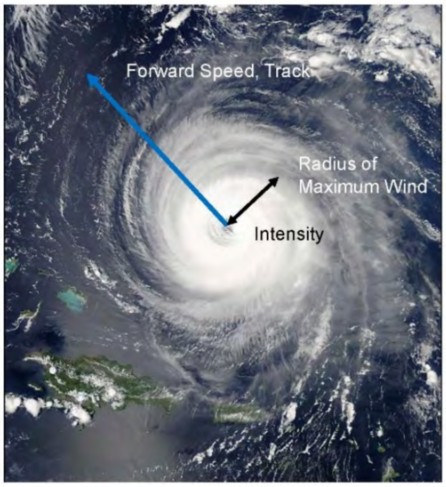
Modeling Hurricane-Driven Storm Surge

- Hurricanes can be numerically simulated through a Monte Carlo analysis evaluating a number of parameters
  - Central pressure deficit
  - Radius of maximum wind
  - Maximum wind speed
  - Storm track
  - Forward speed
- Other parameters can be treated probabilistically, such as the tidal height

Storm Meteorological Parameters



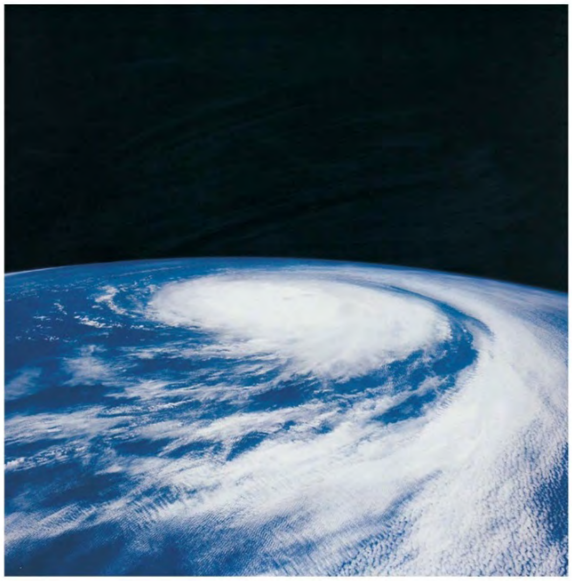
Source: NASA Earth Observatory Image

Joint Probability Method

- The Joint Probability Method (JPM) combines the simulated hurricanes with a model for the storm surge produced by the storms
- Monte Carlo analysis performed selecting hurricane parameters for each simulated hurricane
- Range of parameters based on expert judgement from historical hurricane data
  - Correlation between parameters can be explicitly included
- Time point on tidal curve chosen randomly
- Result of the Monte Carlo and storm surge modeling leads to a flood-frequency curve for the site

EPRI Research on JPM

- EPRI is currently conducting research on the use of the JPM to develop a storm surge flood-frequency curve for a site
- This research will be published in 2018



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Using Historical Water Levels to Assess Storm Surge

- Example site from EPRI Report 3002008111 located on the Great Lakes
- Site is not subject to fully formed hurricanes, so using a Joint Probability Method that models the atmospheric parameters is not applicable
- Long history (greater than 100 years) of lake levels is available including paleo data that can extend the record to 4000 years
- Lake buoys provide water level data
- Wave height, period, and direction determined by U.S. Army Corps of Engineers hindcast datasets

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Monte Carlo Simulation for Storm Surge

- Probability density functions (PDFs) created to represent:
  - Initial lake level
  - Storm surge height
  - Wind-wave parameters
- It is not always obvious which PDF provides the best fit to the existing data and which data source is most applicable
  - Logic trees used to weight alternative PDFs and data sources to each parameter
  - Process is similar to what is used by the Senior Seismic Hazard Analysis Committee (SSHAC)
- Monte Carlo simulations used to develop still water level hazard curve and total water level (including wave run-up) hazard curve
  - Sensitivity studies can be run to determine the sensitivity of the analysis results to particular assumptions

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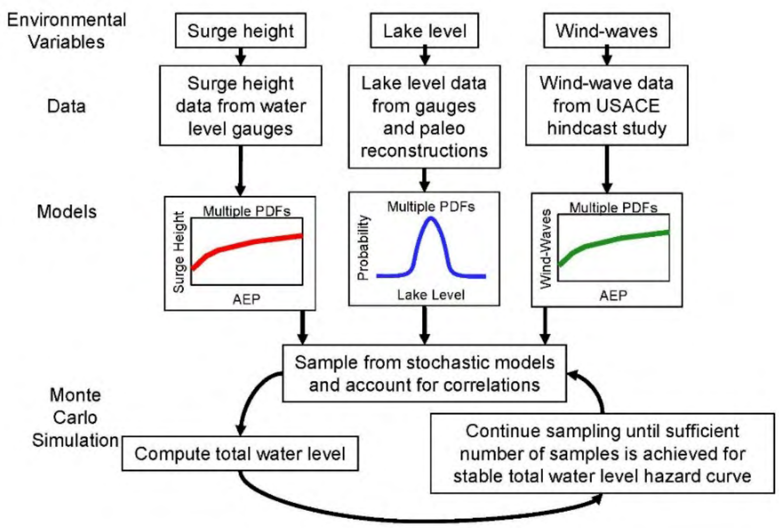
Probabilistic Storm Surge Hazard Assessment Example



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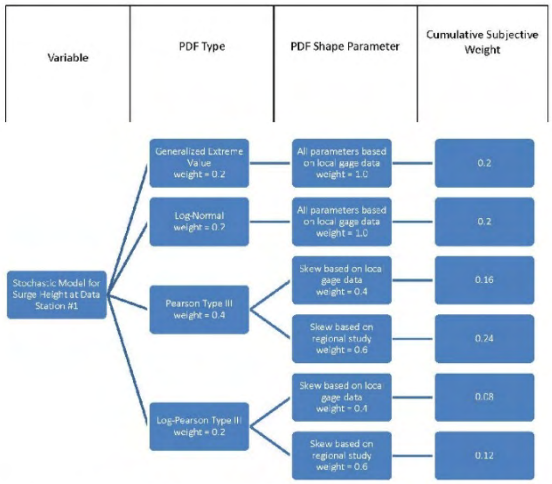
Example Logic Tree to Determine Weighted PDF



Expert judgement and objective criteria used to set weighting parameters

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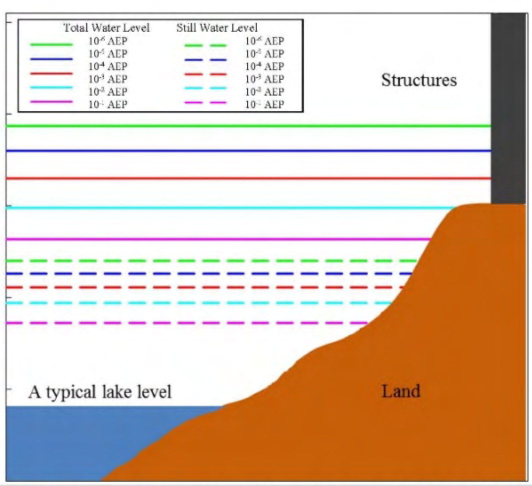
Example Still Water and Total Water Levels



Structures may be impacted by waves at a frequency of about 1X10^{-3}/year

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3.3.3.2.3 Questions and Answers

Question:

I'm very interested and you didn't mention the word seiche. For your lake levels did you think in terms of that? And then a follow-up quick question is, we heard from Ruby Leung this morning about some estimates of how climate may change the Great Lakes, she didn't bring up but the idea of intense storms on the Great Lakes that would enhance the storm surge and the seiche level. Do you want to comment?

Response:

Okay so for those who don't know: seiche is a periodic motion of a closed body of water. Now I know that the Great Lakes typically use the term seiche inappropriately for anything that looks like a large increase in water level. That particular approach: basing it on historical water levels cannot distinguish between a storm surge versus a seiche from any other means. Okay so this approach would actually capture both of those. If you got your data from something different, it may not include seiche. One of the complications with external flooding is that we break it neatly into different criteria. They're not always so easily distinguished. Local intense precipitation and riverine flooding can be happening at the same time. So, you have to be careful when you do your analysis and what you are encompassing and what you're not. In order to make sure that you're not leaving something behind that you're not including. So, like I said, seiche would be included in that. If the data for whatever reason had that excluded, you would have to do a separate analysis on that EPRI has not done any research specifically for seiche or tsunami at this point for hazard assessment.

Audience Comment:

With regard to seiche, whether it's captured or not will depend upon the time scale. Because when you process the wind wave data, you're always going to use some sort of time scale that you're using. If that seiche is within that time scale, you'll capture it but if that seiche is something with a really long period that might not get captured.

Response:

With regard to climate change, this analysis did not include adding additional information to predict the future. Typically, when we do probabilistic risk assessments, you are assessing the as-built as-operated plant, so you are looking at today's conditions and so should you add something to say in the next 20 years I expect this to get worse? I'm not sure what's appropriate there. Maybe you should be updating your model every time you update it and maybe increasing the probability as you go along. It's a good question. I don't have a good answer for it. I think it's definitely something we need to consider, but we need to take into account that we're trying to assess today's risk when using a probabilistic risk assessment and unless the application is looking into the future.

3.3.4 Day 1: Session 1D - Leveraging Available Flood Information I

Session Chair: Nebiyu Tiruneh, NRC/NRO/DLSEA/RHMB

Research to develop the means by which staff can leverage available frequency information on flooding hazards at operating nuclear facilities to support the SDP.

3.3.4.1 Flood Frequency Analyses for Very Low Annual Exceedance Probabilities using Historic and Paleoflood Data, with Considerations for Nonstationary Systems Karen Ryberg*, Ph.D., Kelsey Kolars, and Julie Kiang, Ph.D., U.S. Geological Survey (Session 1D-1; ADAMS Accession No. ML17355A090)

3.3.4.1.1 Abstract

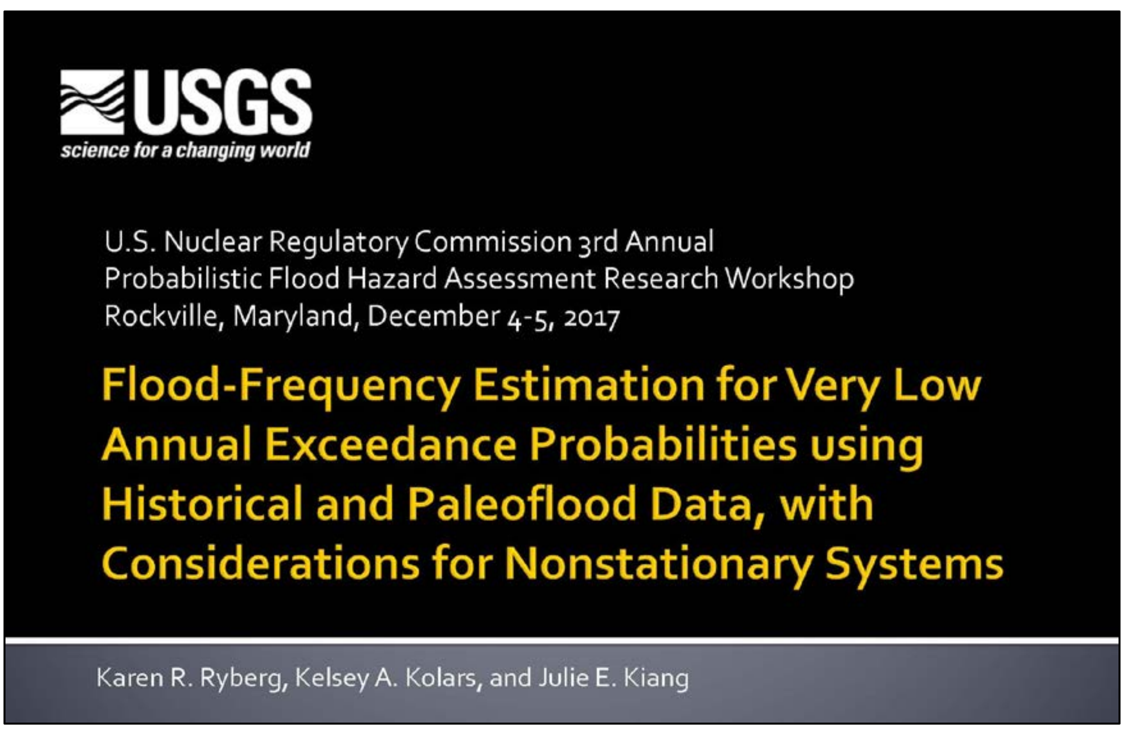
Exceptionally rare flood events may have an annual exceedance probability (AEP) of 0.0001 or lower, meaning the average recurrence interval may be 10,000 or more years. Standard methods for statistical estimation of flood frequency rely on a systematic streamflow record, which provides a time series of annual peak streamflow (peak flow). While few long-term streamgages in North America provide records of peak flow more than 125 years in length, estimation of peak flows with very low annual exceedance probabilities is needed to accurately portray risks to critical infrastructure, such as nuclear power plants. Uncertainties are large when extrapolating magnitudes of extremely rare events from a streamflow record that is much shorter. The addition of historical data (data outside the systematic record, yet within the period of human record, such as newspaper accounts that can be translated to flood magnitudes) or paleoflood data (information about flood occurrence or magnitude from sources like sediment deposits or tree rings) can inform flood-frequency estimates and, in some cases, reduce error bounds. In other cases, the paleoflood information can appear to come from a different population than the systematic record.

An additional complication for flood-frequency analysis is the need to satisfy the assumption that the time series is stationary; that is, peak flows vary around a constant mean within a particular envelope of variance. As concerns about land-use change and anthropogenic climate change have increased, and our understanding of natural systems has improved, we have learned that the stationarity assumption is sometimes inappropriate. The computation of flood frequencies under nonstationarity remains an active area of research without a consistent approach for dealing with nonstationarities.

Flood magnitudes were calculated for select North American sites with systematic records and historical and paleoflood information using U.S. Geological Survey software, PeakFQ (version 7.2.22429) which has been extended to provide estimates of peak-flows with AEPs as low as 0.000001. (The extended output is intended only for use in special purpose studies of exceptionally rare events. The extended output should not be used for typical flood-frequency studies where the interest is in AEPs in the range of 0.1 to 0.005.) PeakFQ analysis used the expected moments algorithm, which allows inclusion of nonstandard flood information, such as intervals. PeakFQ also identified potentially-influential low floods (PILFs) that may represent nonstationarities. Use of EMA with the identification of PILFS means that the low floods were censored and had little or no influence on estimates on the high end of the flood-frequency distribution.

Results will be presented for the Red River of the North at Winnipeg, Manitoba, a site with a long systematic record, historical peaks, and paleoflood information. The presentation will demonstrate how additional flood knowledge beyond the systematic streamflow record affects estimation of low AEP floods and error bounds. The Red River also has some nonstationary features (abrupt changes, serial correlation, and an increasing trend in flow) that violate the underlying assumptions for flood-frequency analysis. These nonstationarities and their implications for the estimation of flood events will be discussed along with possible adjustments.

3.3.4.1.2 Presentation



The Problem

Exceptionally rare flood events may have an annual exceedance probability (AEP) of 0.0001 or even lower; meaning the average recurrence interval may be 10,000 or more years.

Yet, estimation of these flood-flow frequencies is needed to accurately portray risks to critical infrastructure, such as nuclear power plants

USGS

The Problem

Standard methods for statistical estimation of flood frequency rely on the systematic streamflow records (few of which extend beyond 125 years).

Uncertainties are large when trying to extrapolate magnitudes of extremely rare events.

The addition of historical and paleoflood data can help extend the records of floods.

USGS

The Problem

An additional complication for flood-frequency analysis is the underlying assumption that the flood series is stationary —

data are stationary, independent and identically distributed, and lack any long-term persistence or autocorrelation.

USGS

Nonstationarity

- Nonstationarity refers to annual peak-flow values whose mean, variance, or distribution changes either gradually or abruptly over time.
- Nonstationarities may be attributed to one source (regulation, land-use change, climate), but often times are the result of a mixture, making detection difficult.
- Random variation at a site can be "detected" as a nonstationarity.

USGS

Assumption of Stationarity in Flood-Frequency Analysis

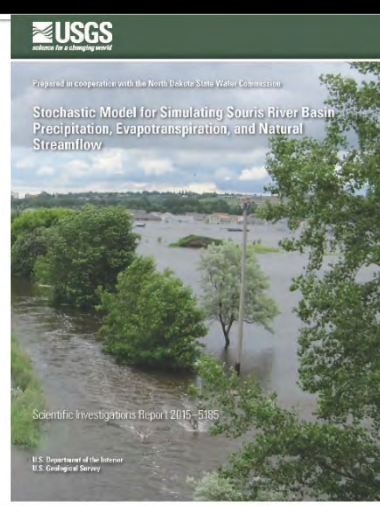
As more information becomes available through historical and paleo records, there have been questions about whether the hydrologic system ever was stationary.

USGS

Nonstationarity in the Interior of the Continent

"Results demonstrate that the 89 year period of observational record in this region is a poor representation of the long-term properties of the hydrologic regime, and shorter periods, e.g., 30 years periods, are by no means representative."

Razavi and others, 2015, Toward understanding nonstationarity in climate and hydrology through tree ring proxy records, Water Resources Research, 51, 1813–1830, doi:10.1002/2014WR015696.

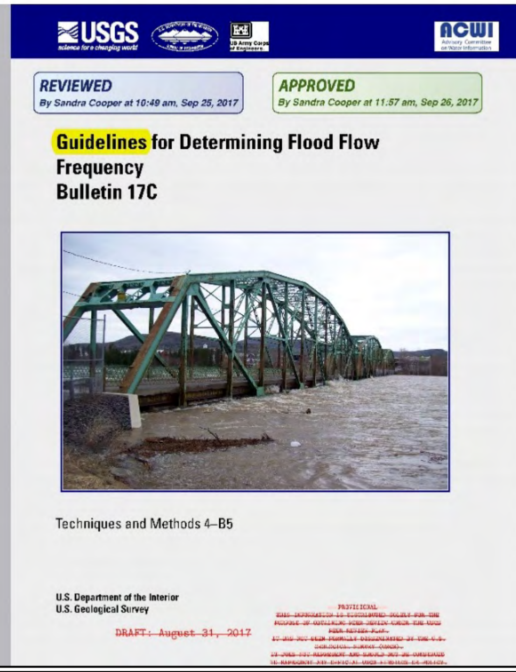


Kolars and others, 2016, Stochastic model for simulating Souris River Basin precipitation, evapotranspiration, and natural streamflow: U.S. Geological Survey Scientific Investigations Report 2015–5185, 55 p., http://dx.doi.org/10.3133/sir20155185.

USGS

Bulletin 17C

Approved for publication by U.S. Geological Survey https://acwi.gov/hydrology/Frequency/b17c/bao-approval-copy_IP-065340_Cohn-Bulletin17c-09-25-2017.pdf



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Flood-Frequency Analysis with Paleoflood Data

PeakFQ and Expected Moments Algorithm

- Nonstandard flood data may be used with PeakFQ and the expected moments algorithm (EMA), including flood interval estimates and flood thresholds.
- For years with missing data in which some flood information is known, perception thresholds may contribute to additional information about the frequency of large floods.
- These thresholds are used to describe knowledge about a particular year or series of years for which a particular value would have been observed or recorded if it has occurred.

USGS

In Bulletin 17C Context

- Information that could be converted to a streamflow estimate
  - Interval estimate indicating flood was between 5,000 and 7,000 cfs
  - Estimate indicating flood was greater than 8,000 cfs (such as when a bridge was overtopped and one can estimate a gage height-streamflow relation)
  - Estimates indicating floods of size X have not occurred for Y number of years
  - Estimates indicating flood less than a value (qualification code 4)

Historical Peaks

- Peaks that occur within the human record, but outside of a systematic gaging record.
  - Newspaper accounts
    - Flood overtopped a bridge by X feet
    - Flood was the highest since 1876 according to "old-timers"
    - Flooding reached First Street
- These are often biased toward large floods, but not to be confused with the largest flood in "history"

Example of Sources of Paleoflood and Historic Data

- Red River of the North at Winnipeg, Manitoba
  - Long-term gage
  - Three large historic flood point estimates determined by Canada Department of Resources and Development
  - Historic flood interval estimates determined by historian based on Provincial records, Hudson's Bay Company diaries, and other sources
  - Tree-ring based flood estimates
  - Tree-ring based flood threshold and indicator that largest flood in 350 years was in 1826

USGS

Paleoflood Data

- Paleofloods refer to those that occurred before a human record and are determined using geologic and physical evidence.
  - Changes to flood plains and terraces
  - Slackwater deposits
  - Flood bars
  - Tree scars, tree ring anomalies, tree age
  - Erosional scars

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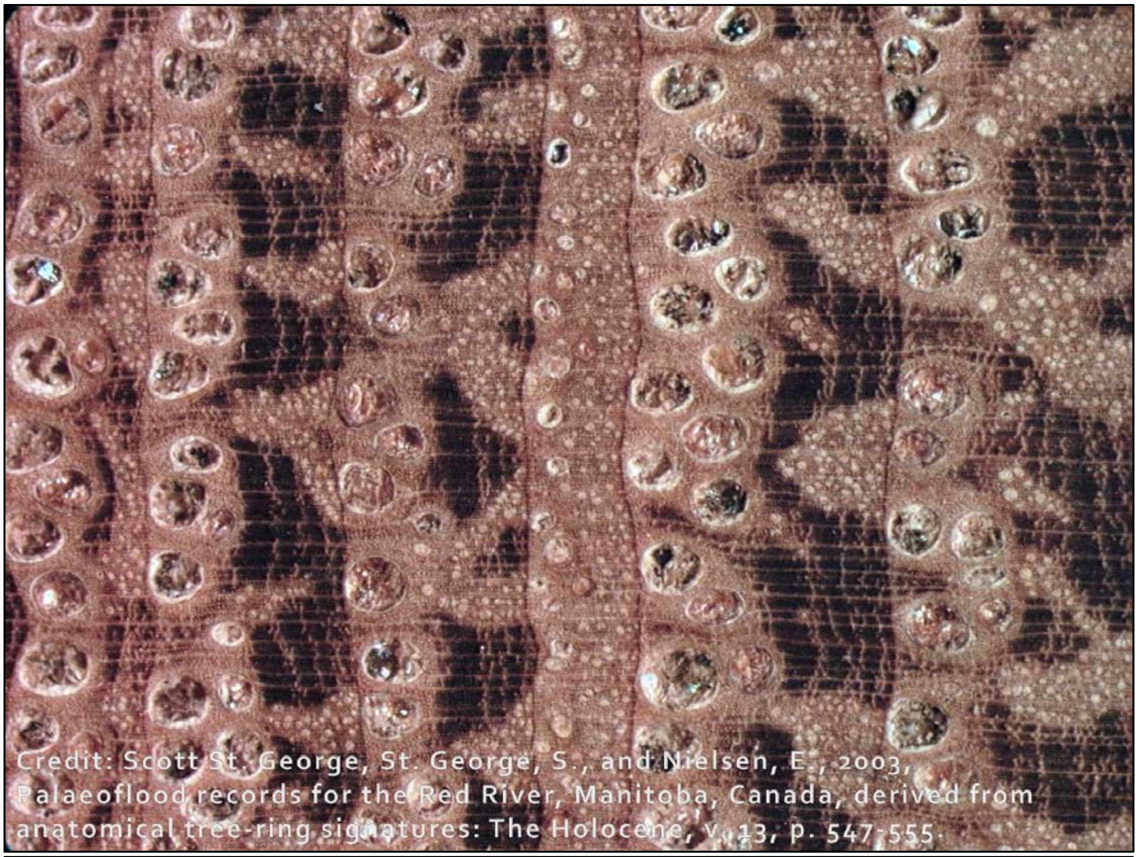

Credit: Scott St. George, St. George, S., and Nielsen, E., 2003, Palaeoflood records for the Red River, Manitoba, Canada, derived from anatomical tree-ring signatures: The Holocene, v. 13, p. 547-555.

PeakFQ Example

Red River of the North at Winnipeg, Manitoba, Canada

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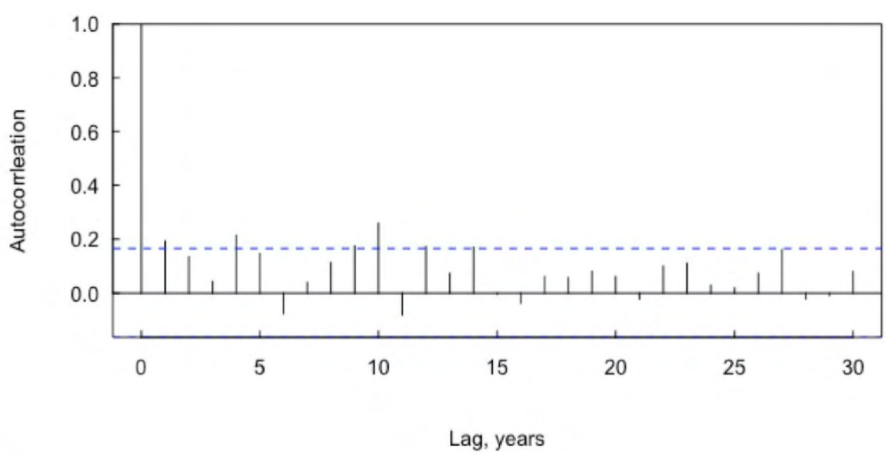
Need Exploratory Data Analysis First

- Search for nonstationarities
  - Autocorrelation/serial correlation
  - Change points/step trends
  - Trends

The Red River Has It All

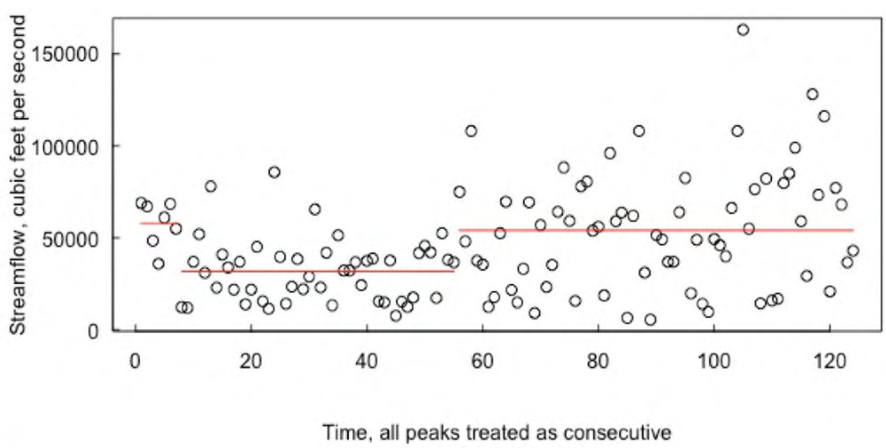


How Much Autocorrelation is Too Much?

- One implication is that the effective length of the record is not as long as it appears—there is redundancy in the information.
- Burn and Goel (2001) analyzed 117 years of record for this site and determined that it was equivalent to an independent record of 45 years.
- Autocorrelation has the effect of increasing the uncertainty of flood-frequency estimates.

USGS

The Red River Has It All



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When are one or more change points concerning?

- Change points are a violation of the independent and identically distributed data assumption.
- PeakFQ can identify potentially-influential low floods (PILFs; small values that would have a large influence on the fit of the flood-frequency distribution), censor them, and then focus the distribution fit on the larger floods.

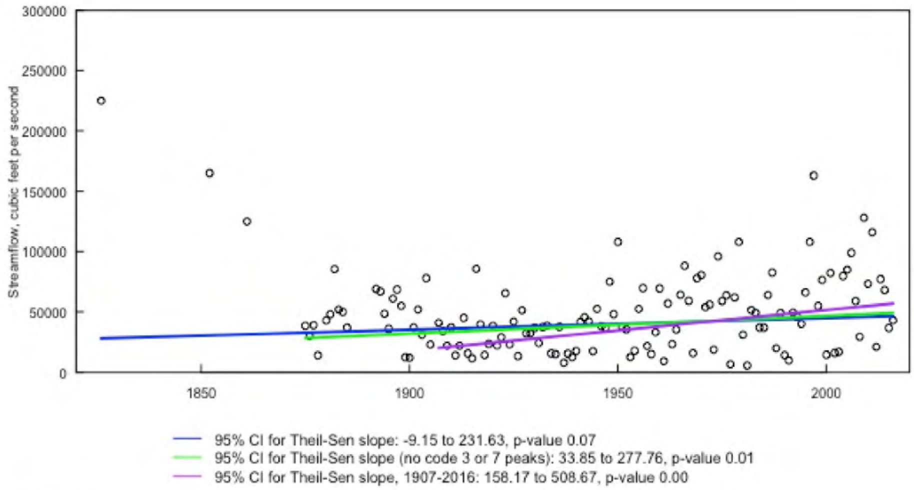
USGS

Red River PILFS

At least some of the floods from the period of relatively lower flows for the Red River may be identified as PILFS, discounting this period in the flood-frequency analysis.

USGS

The Red River Has It All



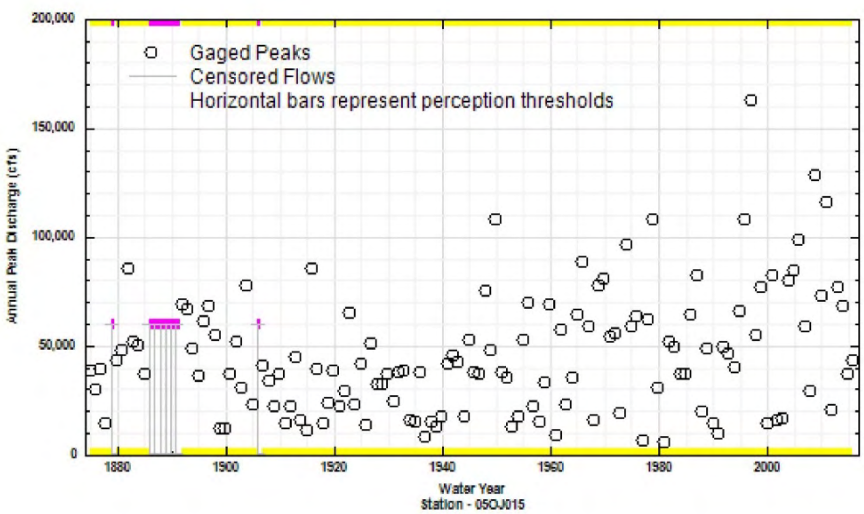
When is a trend a problem?

- In this case, confounded by short and long-term persistence (Nature is Trendy, Hurst phenomenon).
- Is the trend real?
- Persistence violation of Mann-Kendall
  - Many modifications to Mann-Kendall to adjust for persistence
  - Tested these on the Red River, indicated that there is persistence and a significant trend.
    - Do we have a long enough period of record to really say there is a trend?

Flood-Frequency Analysis

USGS

Systematic Data and Perception Thresholds



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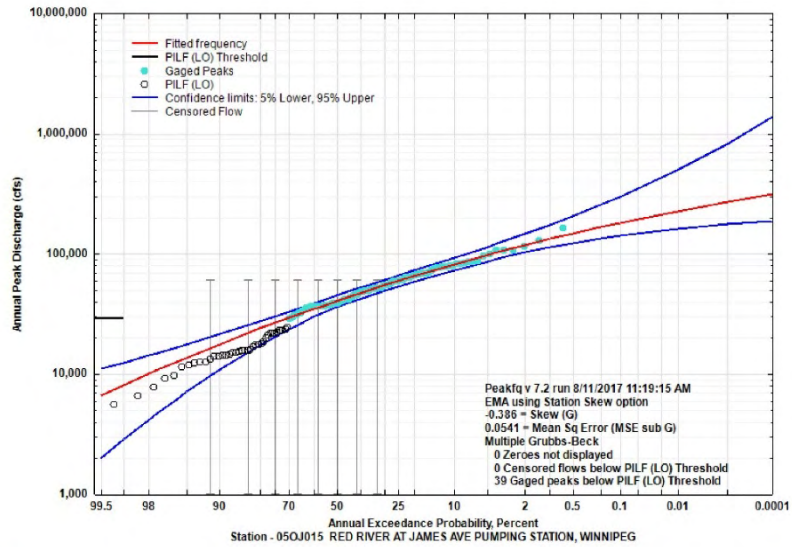
Flood-Frequency Curve – Systematic Record



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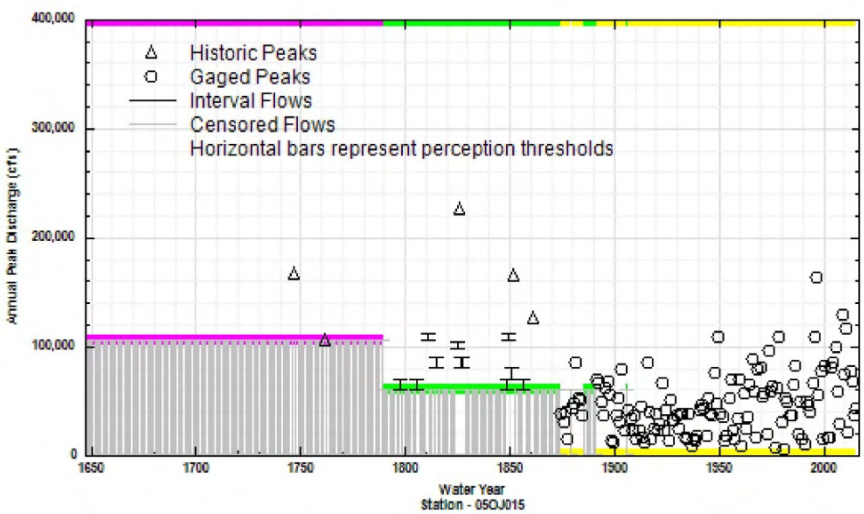
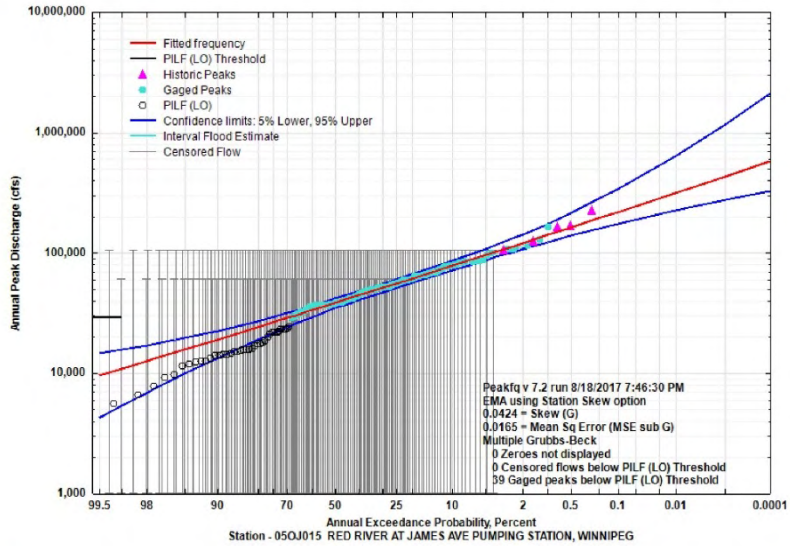
Preliminary Information—Subject to Revision. Not for Citation or Distribution

Systematic and Historic Data, Historic Intervals, Paleo Peaks, and Perception Thresholds



USGS

Flood-Frequency Curve – Systematic and Historic, Historic Intervals, and Paleo Data



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Red River of the North at Winnipeg

Scenarios

1. systematic peaks (standard at-site analysis);
2. wet period of 1948-2016, based on the change-point analysis;
3. most recent 30 years of data;
4. systematic and historic peaks and interval estimates; and
5. systematic and historic peaks, historical and paleo-derived estimates, and paleo-derived thresholds.

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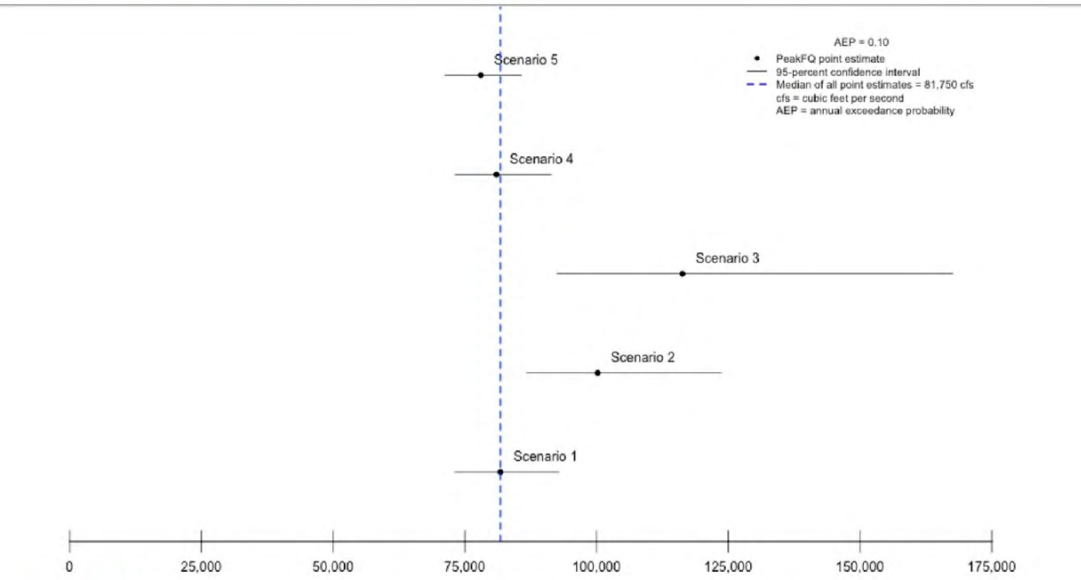
AEP = 0.10



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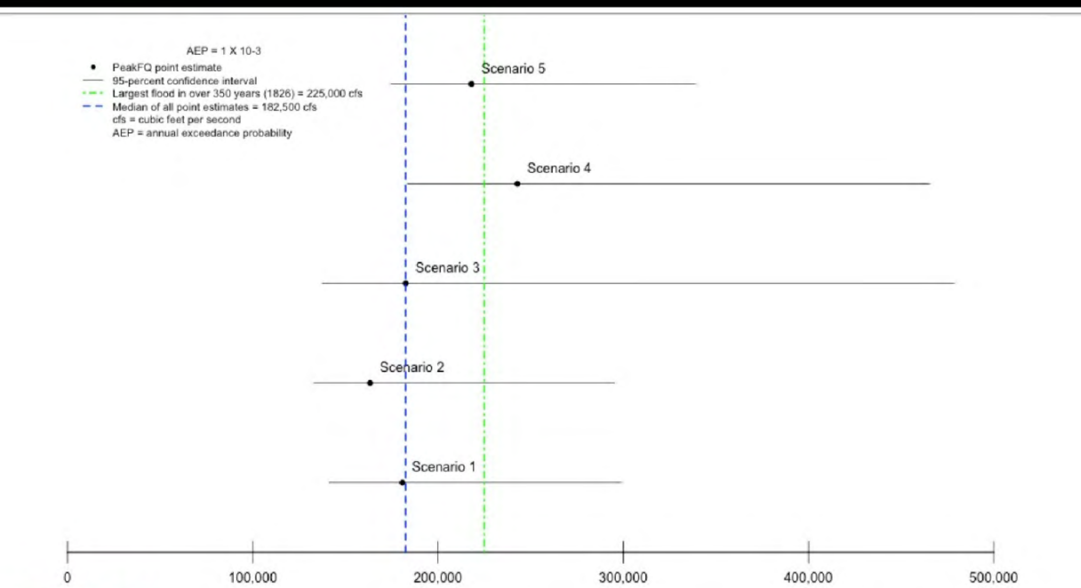
AEP = 0.001



USGS

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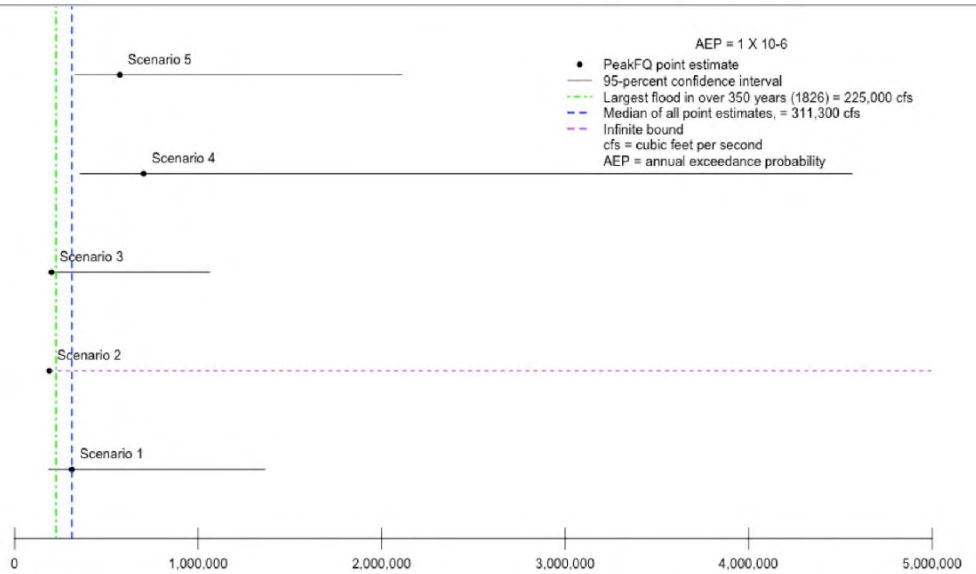
AEP = 0.000001



USGS

Preliminary Information—Subject to Revision. Not for Citation or Distribution

Limitations of EMA-LPIII

- Nonstationarities – active area of research, but no good solution
- Paleo data may help put bounds on very low AEPs
- Paleo data may increase uncertainties – can appear to come from a different population
- In addition to all the statistical assumptions, you are making assumptions about the channel and climate.

USGS

3.3.4.1.3 Questions and Answers

Question:

I have a question about the tree rings. How do you tell the difference between an event in the tree ring record, you know like a large flood, versus a wet season?

Response:

You would have to examine them with a microscope and that is something I've thought quite a bit. Because tree ring analysis is often done to estimate precipitation and a wide ring is a wet year, a narrow ring is a dry year, but if we look at this narrow ring we know this was a very wet year and it resulted in a narrow ring. So, it's one thing to measure the tree-ring width which takes some microscopic work, but you have to go into much more detail microscopic analysis to be able to see evidence for a flood. Also, one of the issues for this by this researcher Scott St. George knowing some very large floods, like the 1826 flood, he could figure out the signal in the tree rings for that and then based on that signal estimates some past floods but his estimate of these floods he says is really a minimum. It should be an interval estimate from this minimum value, but it's not known in this tree ring what is the upper value that you could detect. It would vary with river but there's probably some upper value that might kill the trees or you don't know what the upper limit is, so this really should be an interval estimate but we don't have that upper limit.

Question:

So, then you had actual discharge estimates based upon the tree rings, so then you must have been able to get an inundation level that is associated with that? Correct?

Response:

Yes. So, when you do tree rings it's a whole chronology. You get cores for multiple trees in a stand of various ages and you know that there was a flood in 1997 and you can see that result in tree rings. You know there was a flood in 1850, you line up your tree rings and you can see this consistent signal. We know there was a large flood in 1826, we can see that signal and then going back in time when we don't know much about the floods we look for that same signal. And the degree to which the tree was affected by that and then comparing it to the known floods. And how this ring looked during the known very large floods, the researcher came up with an estimate of flood magnitude. Looking at a variety of sources, stream discharge relationship, modern floods, how those look in the rings.

Question:

So, it’s not just the elevation?

Response:

No.

Question:

To add on to what you're saying before… that it's a lower bound… how it affects the tree ring also depends on when in the growing season the flood occurs. Right? Can there be floods that the tree-ring won't represent because it wasn't adding material at that time?

Response:

Yes. That's a good question. There are a few large floods in this red river series that we know happened. And that there's some interval or point estimates for that that did not show up in the tree-ring series, so this is essentially a minimum estimate for magnitude and a minimum estimate for frequency as well.

Question:

So, can you give similar information from dead trees or did it have to be alive?

Response:

It can be dead trees. For example, there's a researcher in Minnesota that has gone to settlers' cabins. There are many cabins in Minnesota built in the 1800s that have been preserved and ultimately been passed down through families. There's a known date when that cabin was built, and he's gone to those cabins and got them to let him put some holes in the logs. He's developing a tree ring chronology based on that. Also, this researcher, Scott St. George, has gone to the Red River and done some investigation of subfossil logs pulled up from the sediment. It can be hard. You have to compare them to other chronologies, the wet and dry rings, to figure out where they fit because you don't know exactly when they died.

3.3.4.2 Extending Frequency Analysis beyond Current Consensus Limits Keil Neff*, Ph.D., P.E. and Joseph Wright^, P.E., U.S. Bureau of Reclamation, Technical Service Center, Flood Hydrology and Meteorology (Session 1D-2; ADAMS Accession No. ML17355A0901)

3.3.4.2.1 Abstract

This project is part of the NRC Probabilistic Flood Hazard Assessment (PFHA) research plan to support development of a risk-informed approach for addressing flood hazards at nuclear facilities. This work focuses on providing technical guidance for developing extreme flood frequency estimates beyond the current consensus limits (Annual Exceedance Probabilities (AEPs) less than 1×10^{-4}) from the context of the Bureau of Reclamation.

Reclamation , the owner of approximately 370 dams and dikes in the Western U.S., pioneered conducting flood frequency analyses to support dam safety risk-informed decision-making. For Reclamation dam safety risk assessments, flood estimates are needed for AEPs of 1 in 10^4 and down to as low as 1 in 108. Developing credible estimates at these low AEPs generally requires combining data from multiple sources and a regional approach. Reclamation has published methodology and guidance to develop hydrologic hazard estimates over the past quarter of a century. The primary purpose of these published guidelines, procedures, and standards was to

provide state-of-the-practice methodology for developing hydrologic hazard curves (and supporting flood hydrology information) to be used for evaluating facilities, prioritizing dam safety modifications and supporting planning and design decisions.

From a hydrologic perspective, risk estimates require an evaluation of a full range of hydrologic loading conditions and possible failure mechanisms tied to consequences of failure. The flood loading input to a dam safety risk analysis is a hydrologic hazard curve (HHC) that is developed from a hydrologic hazard analysis (HHA). Hydrologic hazard curves combine peak flow, water surface elevation, and volume probability relationships plotted with respect to their AEPs. Information derived in HHAs, including HHCs and associated flow and stage frequency hydrographs, can be used to assess the risk of potential hydrologic-related failure modes including overtopping, internal erosion under various reservoir levels, erosion in earth spillways, and overstressing of structural components.

When evaluating hydrologic hazards, a systematic means of developing flood hazard relationships is needed for risk-based assessments to determine hydrologic adequacy for Reclamation dams. The nature of the potential failure mode and characteristics of the dam and reservoir dictate the type of hydrologic information needed. The selected also considers available hydrologic data, potential analysis techniques, available resources for analysis, and an acceptable level of uncertainty. For some projects, only a peak-discharge frequency analysis may be required; while for others, flood volumes and hydrographs may be necessary. The goal of any hydrologic analysis is to provide hydrologic information to the necessary level (i.e. minimum effort and cost) to make effective dam safety decisions.

To provide flood estimates for a full range of AEPs necessary for dam safety decision-making, it is usually necessary to extrapolate beyond the period of recorded data. The type of data and the record length used in the analysis form the primary basis for establishing a range on credible extrapolation of flood estimates. Streamflow and reservoir data corresponding to current operations and watershed characteristics are data that should be used in FFAs. In higher level projects requiring more effort, data can be adjusted to represent the current conditions and operations to extend series for the entire period of record. The data used provide the only basis for verification of the analysis or modeling results, and as such, extensions beyond the data cannot be verified. The greatest gains to be made in providing credible estimates of extreme floods can be achieved by combining regional data from multiple sources. Thus, analysis approaches that pool data and information from regional precipitation , regional streamflow, and regional paleoflood sources provide the highest assurance of credible characterization of low AEP floods.

The principal components of this work include guidance on data sources and model inputs, probabilistic hydrologic hazard methods, multiple methods and other considerations, and Reclamation case studies. This presentation will provide an overview of what is described in this project including: 1) streamflow and climate data necessary; 2) statistical methods, physically based hydrologic modeling approaches, the Australian Rainfall and Runoff method, and the Stochastic Event Flood Model; 3) mixed population systems, combining multiple methods, and uncertainty ; and 4) Reclamation case studies that encompass the breadth of described probabilistic hydrologic hazard methods.

3.3.4.2.2 Presentation

RECLAMATION

Managing Water in the West

Extending Flood Frequency Curves Beyond Current Consensus Limits

Joseph Wright, Keil Neff
Flood Hydrology and Meteorology Group
Technical Service Center

U.S. Department of the Interior
Bureau of Reclamation

1

Introduction

This project provides information the NRC can use to develop guidance for extending frequency analysis methods beyond current consensus limits for both rainfall and riverine flooding applications.

The focus is describing methods used by Reclamation to estimate flood loadings, which have been developed over the past 20 years. Case studies exemplifying these approaches are also included.

Uncertainty characterization and quantification is also a focus of this project.

Flood Loadings to Support Reclamation Dam Safety Risk Activities

From a hydrologic perspective, risk estimates require an evaluation of a full range of hydrologic loading conditions and possible failure mechanisms tied to consequences of failure.

Hydrologic hazard curves combine peak flow, water surface elevation, duration thresholds, and volume probability relationships plotted with respect to their AEPs.

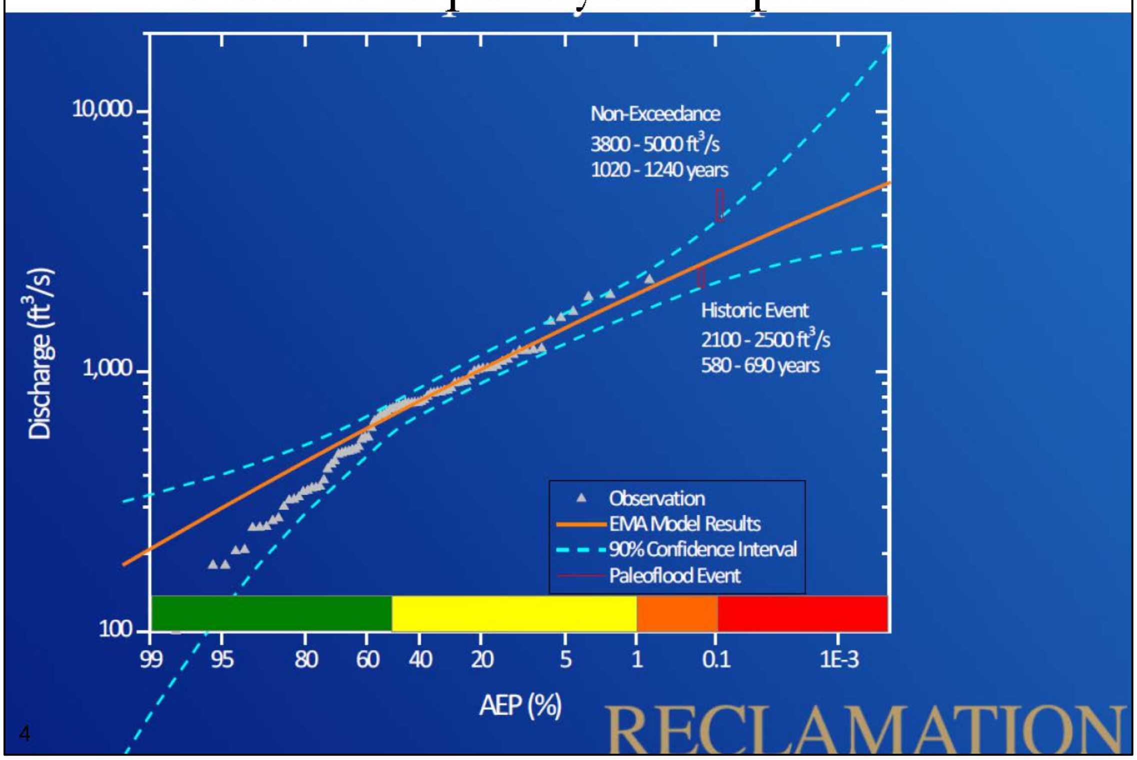
Flood loadings and associated flow and stage frequency hydrographs are used to assess the risk of potential hydrologic-related failure modes.

Reclamation primarily focuses on medium to large catchments in the Western U.S.

RECLAMATION

3

Flood Frequency Extrapolation



RECLAMATION

4

Credible Extrapolation

Type of Analysis	Typical Range	Range (Best)
At-Site Stream Gage	1 in 100	1 in 200
Regional Stream Gages	1 in 500	1 in 1,000
At-Site Stream Gage combined with Paleoflood Data	1 in 4,000	1 in 10,000
Regional Precipitation Data	1 in 2,000	1 in 10,000
Regional Streamflow and Regional Paleoflood Data	1 in 15,000	1 in 40,000
Combinations of regional Datasets and Extrapolation	1 in 40,000	1 in 100,000

Reclamation & Utah State University (1999), Reclamation (2006)

5 RECLAMATION

Level of Effort

The goal of any hydrologic analysis is to provide hydrologic information to the necessary level to make effective dam safety decisions. The available data, possible analysis techniques, resources available, and needs of the decision influence the selection of method(s) used.

Method	Level of Effort	Benefits	Limitations
Graphical Flood Frequency	Low (CR, IE, CAS, FD)	Conservative, incorporates paleoflood information	Estimates far beyond credible extrapolation, conservative
EMA/FLDFRQ3	Low (CR, IE, CAS, FD)	Better estimate of uncertainty, incorporates paleoflood information	Estimates often extended beyond credible extrapolation
Australian Rainfall-Runoff	Low (CR, IE)	Rarer events, very conservative (pragmatic)	Primarily intended for largely deterministic design use, very conservative
GRADEX	Moderate (CR, IE)	Rarer events, conservative	Assumption of all rainfall to runoff, little physically-based modeling
Regional Precipitation Frequency	Moderate (IE, CAS, FD)	Better estimated of uncertainty, still conservative	Improved estimate of precipitation frequency, limited by AEP neutrality
Stochastic Rainfall-Runoff Modeling	High (IE, CAS, FD)	Currently the best estimate of uncertainty, uses information from statistical frequency methods, physical understanding of driving factors/ processes	Extremely rare extrapolation is still uncertain and full range of aleatory variability and epistemic uncertainty is not understood, difficulties calibrating to extreme events

6 RECLAMATION

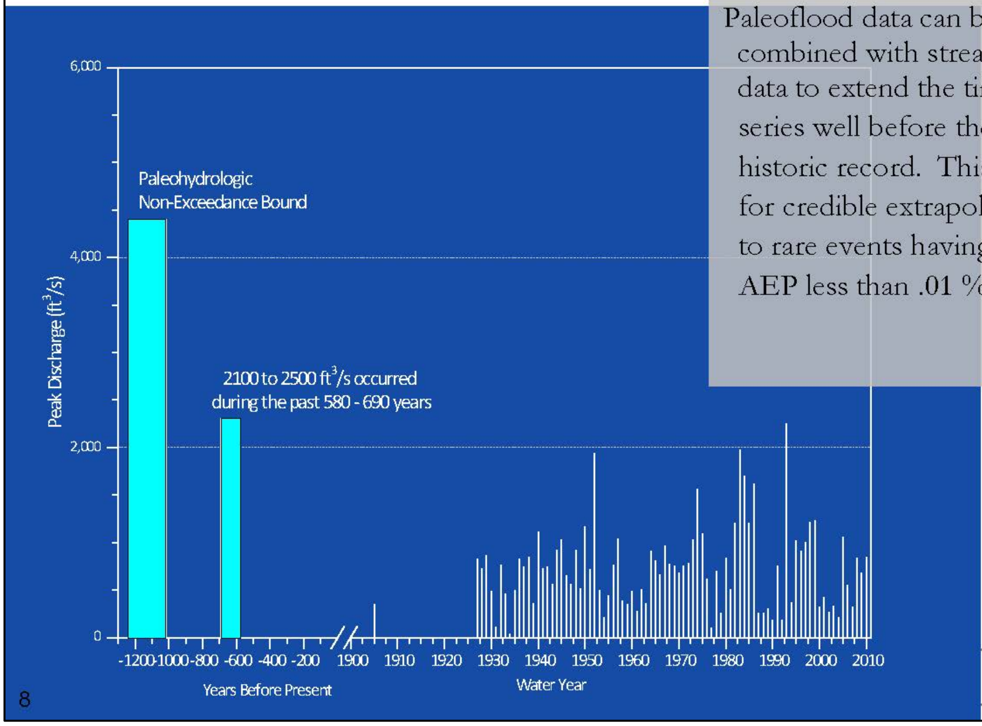
Data Sources

The sources of information used for flood hazard analyses include streamflow, precipitation, and paleoflood data.

Data Source	Level of Effort (Cost)	Analyses
Public Data Sources - Precipitation (e.g. NOAA, PRISM, NCEI)	Low (generally free)	Precipitation frequency (L-moments, Bayesian); storm templates
Public Data Sources – Gaging Stations (e.g USGS, Reclamation)	Low (generally free)	EMA, FLDFRQ3, rainfall-runoff modeling, graphical approach
Public Data Sources – GIS (e.g USGS, NRCS, states)	Low (generally free)	Rainfall runoff-modeling
Regional Paleoflood Information	Moderate (generally free)	EMA, FLDFRQ3, graphical approach
Site-Specific Paleoflood Stratigraphy	Moderate (moderate)	EMA, FLDFRQ3, graphical approach
Detailed Paleoflood Information	High (high)	EMA, FLDFRQ3, graphical approach
LiDAR Collection	High (high)	Paleoflood information, H&H modeling

7 RECLAMATION

Incorporating Paleoflood Data

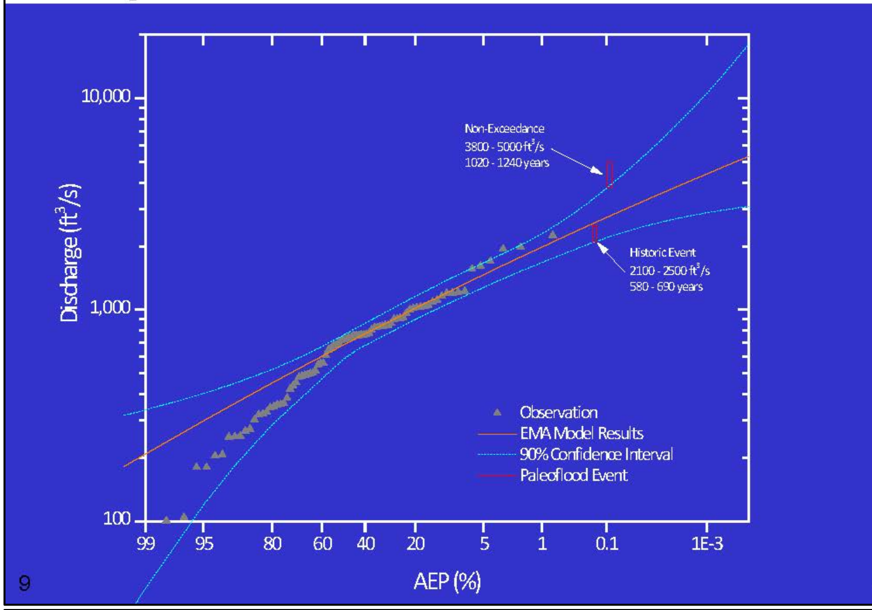


Paleoflood data can be combined with stream gage data to extend the time series well before the historic record. This allows for credible extrapolation to rare events having an AEP less than .01 %

8 RECLAMATION

Low Level Analyses

Reclamation will typically spend 5-10 days for some preliminary analyses (CRs, feasibility level, etc). This often includes EMA with regional paleoflood information. ARR (frequency PMF) is often used to deal conservatively estimate beyond credible extrapolation.

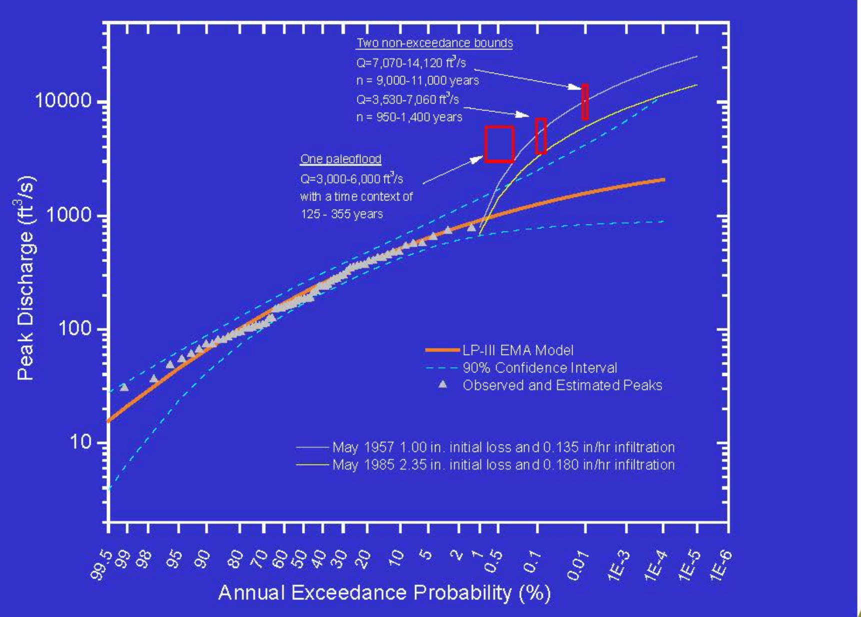


ATION

9

Moderate Level Analyses

15-45 day efforts are often applied to Issue Evaluation, Corrective Action, and Final Design studies (and some high level Comprehensive Reviews).



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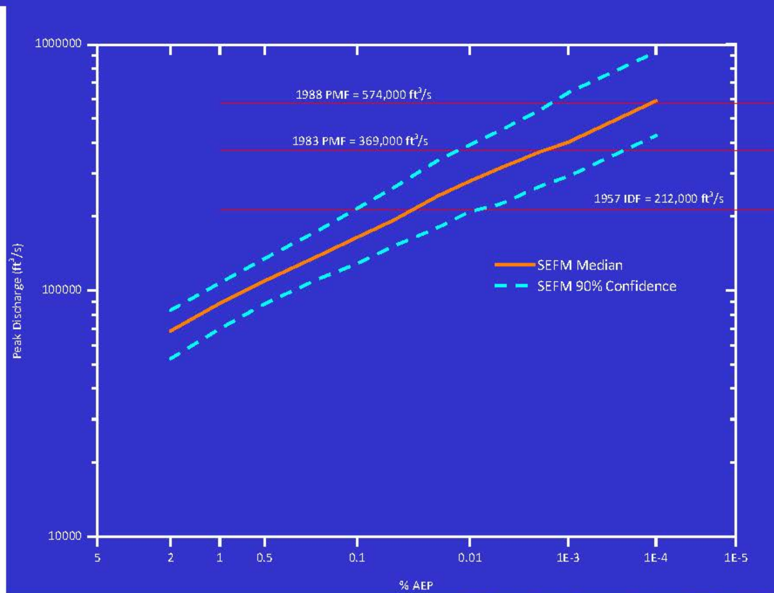
10

High Level Analyses

When the hydrologic risk at a facility may require expensive mitigation (i.e. operations, mechanical, construction risk reduction measure alternatives), studies often require extensive time, effort, and cost to produce flood estimates.



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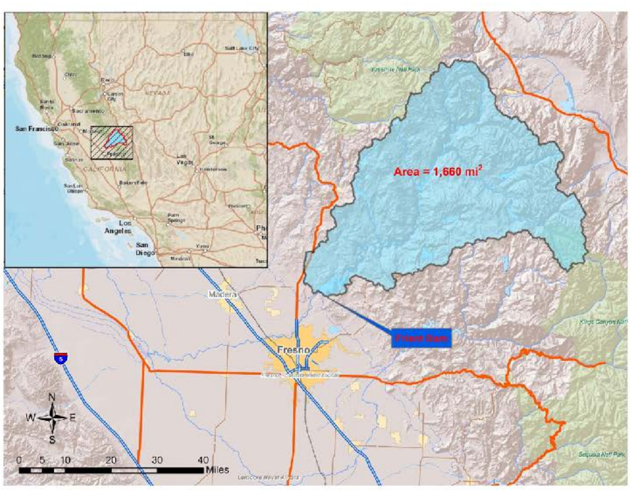
RECLAMATION

Case Study – Friant Dam HHA

This study provided a detailed probabilistic flood loading analysis used to quantify risks associated with various failure modes. This was accomplished by developing flood frequency hydrographs using a stochastic rainfall-runoff model (SEFM).



Structural Height of 319 feet

One 100x18 ft Drum Gate

Two 100x18 ft Obermeyer Gates

Spillway Capacity is 83,000 ft^3/s

Combined Outlet Work Capacity is 17,000 ft^3/s

Controls 1,660 ft^3

11 Upstream facilities (six of which are large dams)

12

RECLAMATION

Stochastic Rainfall-Runoff Model

- Develop physical based 1-dimensional rainfall-runoff using hydrologic runoff units (HRU's)
- Estimate a precipitation frequency curve using the L-Moments method of regional statistics
- Randomly sample the frequency precipitation curve as well as a storm pattern to determine an annual maximum storm event
- Randomly determine the initial model conditions
- Repeat steps 3 and 4 to develop a simulate time-series of maximum flood events
- Fit a statistical distribution to the time series of annual maximum events

RECLAMATION

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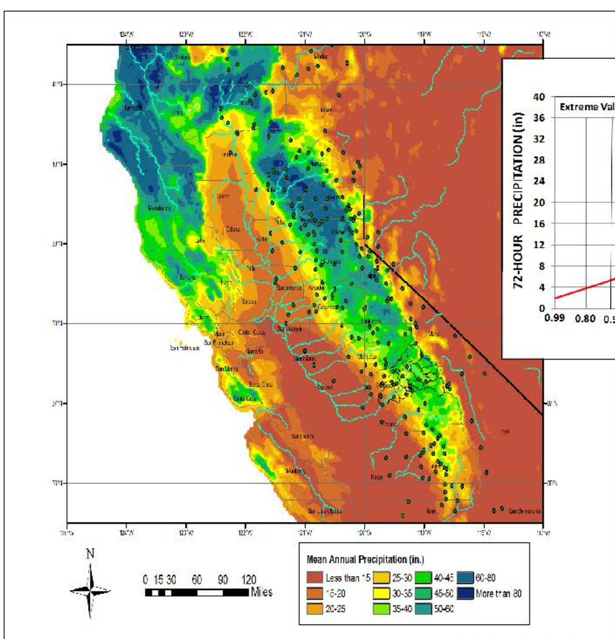
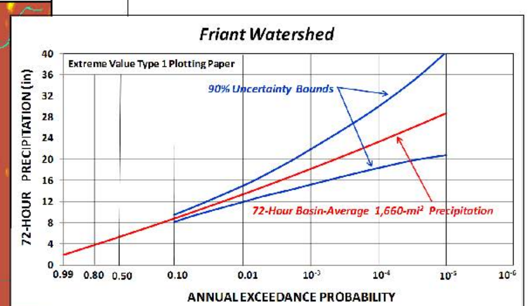
Regional Precipitation Analysis





RECLAMATION

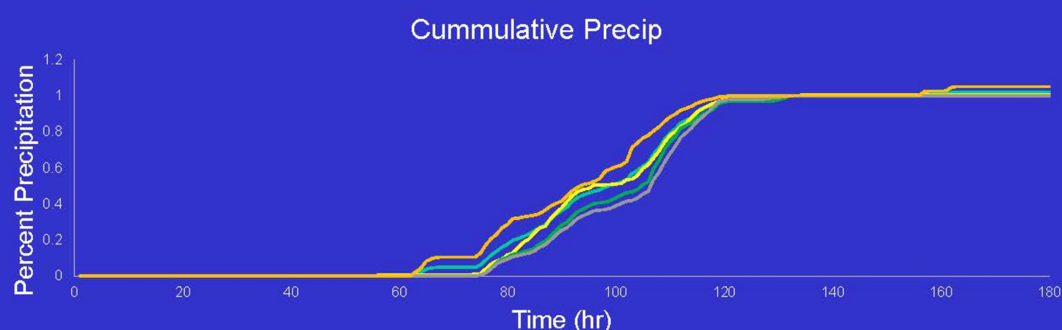
14

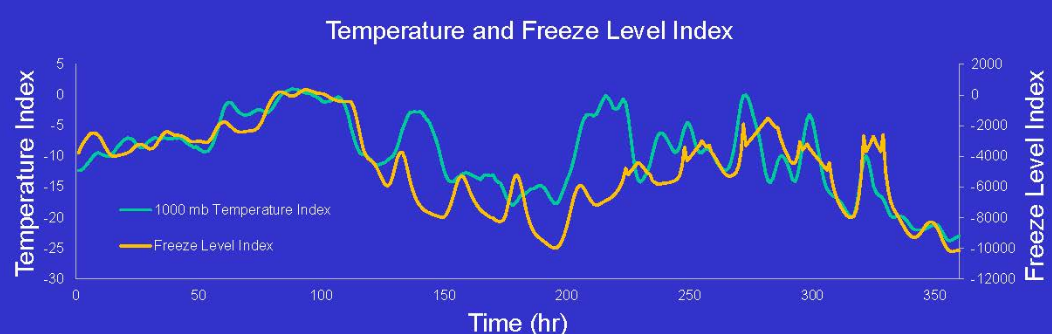
Spatial and Temporal Storm Patterns

Storm	72-hr Precipitation	Use
November 13-22, 1950	10.58	Calibration/Production
December 18-27, 1955	15.09	Calibration/Production
February 3-17, 1962	9.56	Production
January 29 - February 7, 1963	14.91	Calibration/Production
December 17-31, 1964	5.69	Production
December 1-11, 1966	9.56	Production
January 18-22, 1969	10.86	Production
January 23-29, 1969	7.56	Production
September 1-10, 1972	1.67	Calibration
September 1-10, 1978	3.63	Calibration/Production
January 9-19, 1980	8.97	Production
Sepetember 23 - October 2, 1982	4.28	Calibration/Production
February 12-21, 1986	8.78	Production
March 8-18, 1995	9.84	Production
Dec 29, 1996 - Jan 7, 1997	7.29	Calibration/Production
November 6-16, 2002	7.15	Calibration/Production
Dec 26, 2005 - Jan 9, 2006	7.88	Production
December 15-24, 2010	11.2	Production

15 RECLAMATION

Stochastic Storm Template





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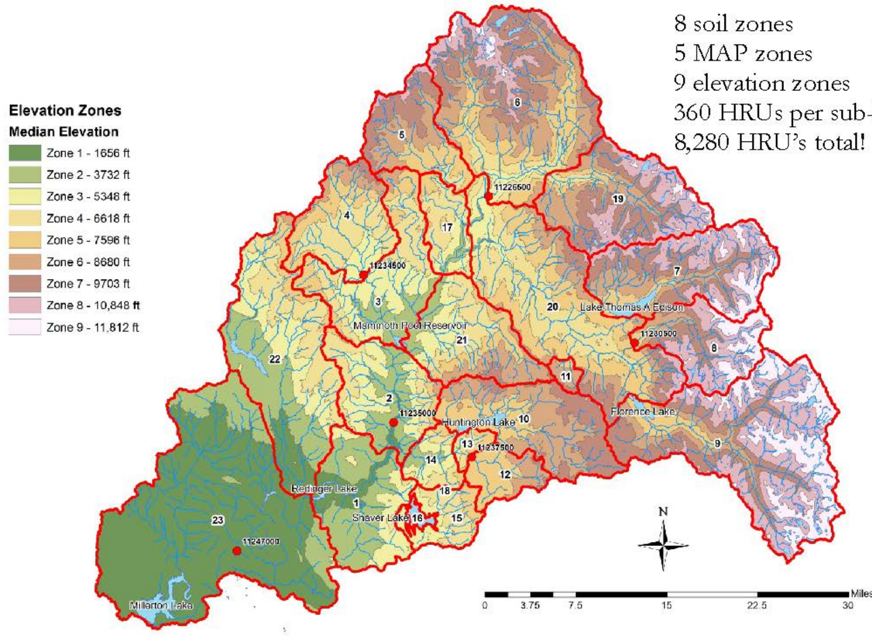
Physical Based Model



8 soil zones
5 MAP zones
9 elevation zones
360 HRUs per sub-basin
8,280 HRU's total!

RECLAMATION

17

Calibration

- 8 Historic Flood Events were used in Calibration
- Friant is a mixed population (rain and snowmelt) system – the maximum annual rainfall didn't always yield the maximum annual flood
- Fall events were used to calibrate high elevation basins because they represented snow-free ground
- Runoff calibration was performed from the upstream basins to the downstream basins
- Adjustments were made to the routing parameters and freeze level offsets to better fit the peak-discharge frequency

RECLAMATION

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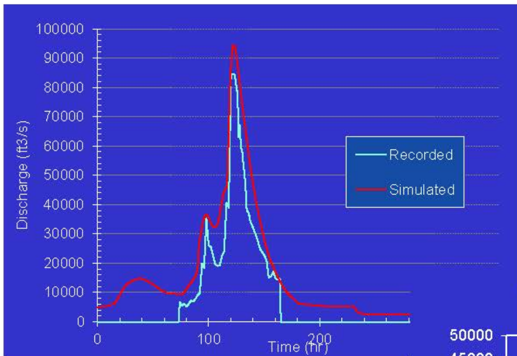
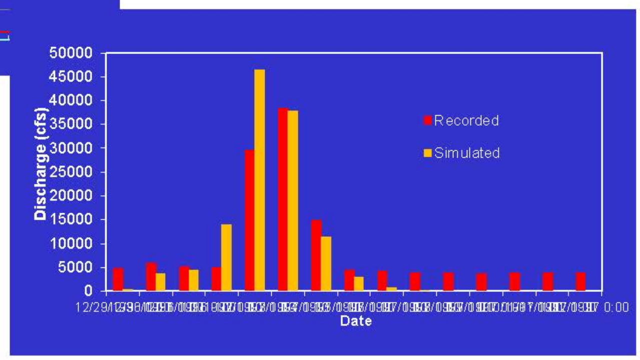
Calibration





RECLAMATION

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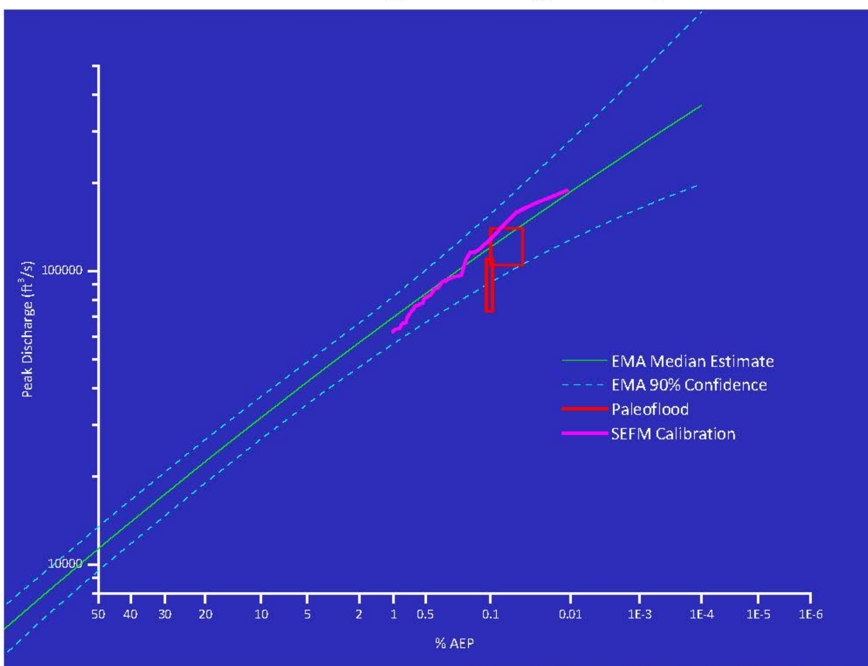
Peak-Discharge Frequency Calibration



RECLAMATION

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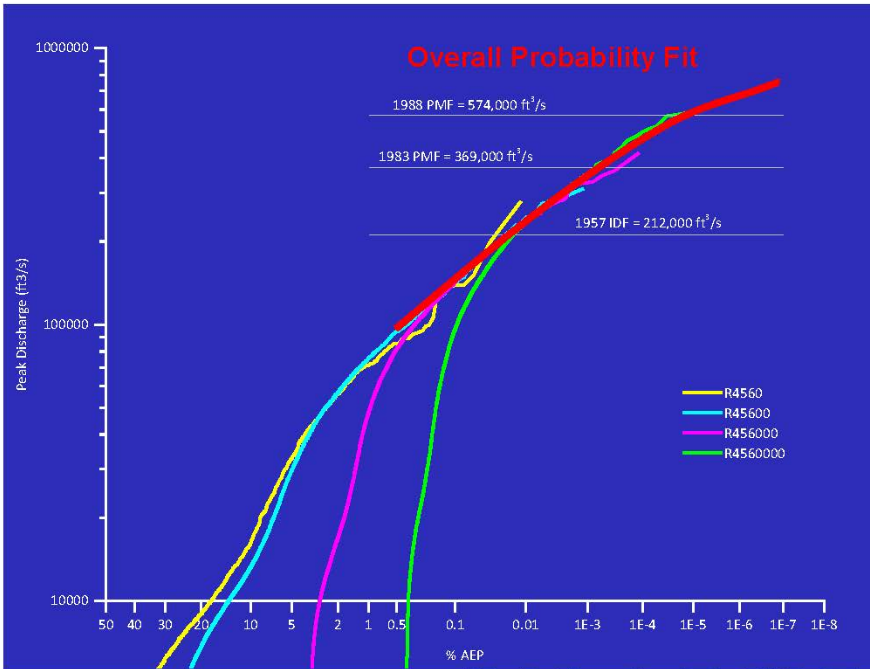
Peak-Discharge Frequency



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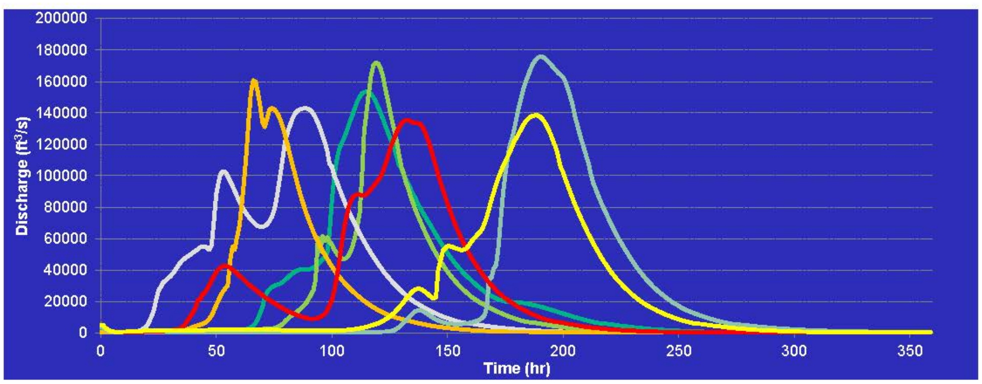
RECLAMATION

Friant Inflow Hydrographs that result in 1,000-yr RWSEL



Rank	AEP (%)	Simulation Number	Init WSEL (ft)	Peak Discharge (ft^3/s)	Total Volume (ac-ft)	Peak Discharge Rank	Total Volume Rank
454	0.0995	5735	531.2	153,396	684,560	644	399
455	0.0997	7021	550.4	172,089	502,242	424	1178
456	0.0999	2540	504.1	142,907	730,048	814	306
457	0.1001	659	563.3	160,704	460,092	540	1531
458	0.1003	3094	485.0	175,883	711,248	387	338
459	0.1006	5992	557.6	135,378	673,066	980	428
460	0.1008	10596	537.0	138,460	661,433	919	454

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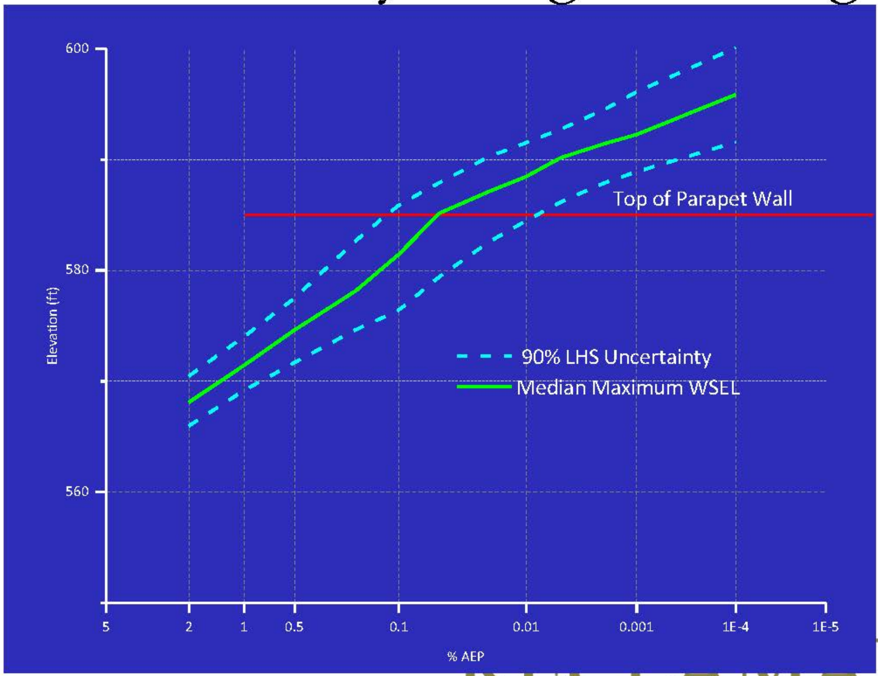
RECLAMATION

Friant Hydrologic Loading



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RECLAMATION

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RECLAMATION

3.3.4.2.3 Questions and Answers

Question: So, I noticed some of your graphs, the scale on the x-axis, if I take out the percent, went as far as 10 to the minus 10 per year, which is double the age of the earth… but the graph didn't go that far. But some of your lines go up to about 10 to the minus 6 per year, some of them stop at 10 to the minus 4 per year. I want to know, from Reclamation's standpoint, at which point…where do you stop being concerned or do you. As you're going lower and lower in frequency and say below this …we're going to screen that out because it's too low a risk to consider?

Response:

Well first of all, we would never go 10 to the minus 10. So, I think Kyle had a slide up there that showed incredible extrapolation under the perfect conditions, all the planets come aligned, and everything and your data is just perfect, you can go to maybe a hundred-thousand-year event. When we're looking at EMA curves with paleo flood data if we have a really, really good data set, I prefer to cut them off at about a twenty-thousand-year event, maybe a fifty thousand if the risk analysis justifies it. When we get beyond that, without any kind of a stochastic type approach, we tend to lean towards a pragmatic approach and that's why I like the Australian Rainfall Runoff Method (ARR). I like to call ARR our frequency PMF's because basically we're just drawing a line from a hundred-year preset to a PMP that we assume some probability to and we're just using that to scale a PMF hydrograph. And it's just a conservative, pragmatic approach that if we say that the dam can handle that then you're probably okay. SEFM… I don't think we've ever done one and that goes beyond a 1-million-year event, and when we do that we now like to incorporate some uncertainty in that and we are working on how to incorporate uncertainty in our overall risk analysis. So hopefully that answers your question.

3.3.4.3 Development of External Hazard Information Digests for Operating NPP sites Kellie Kvarfordt and Curtis Smith*, Ph.D., Idaho National Laboratory (Session 1D-3; ADAMS Accession No. ML17355A092)

3.3.4.3.1 Abstract

The original name of this project was Development of Flood Hazard Information Digests for Operating NPP Sites, and the original objective and tasking of the project was for Idaho National Laboratory (INL) to develop, demonstrate, and help populate a database architecture for Flood Hazard Information Digests. The resulting web application facilitates gathering, organizing, and presenting a variety of flood hazard data sources. However, the database is currently undergoing expansion to include other external hazards such as seismic and high wind hazards, extreme temperatures, and snow/ice loads. This expansion will support the Commission directed activity to enhance agency processes for ongoing assessment of natural hazards information. Thus, a more accurate name for the project and digest application is now External Hazards Information Digest (EHID).

The goal of the project is to provide information and tools to support external event analysis, particularly the risk-informed aspects of the Significance Determination Process (SDP). Under the SDP the use of probabilistic external hazard information and insights is an important input in the determination for follow-up inspection actions and resource allocation, and risk-informing of licensing actions. However, NRC staff has had to improvise and only use probabilistic external hazard estimates on an ad hoc basis, in a limited manner.

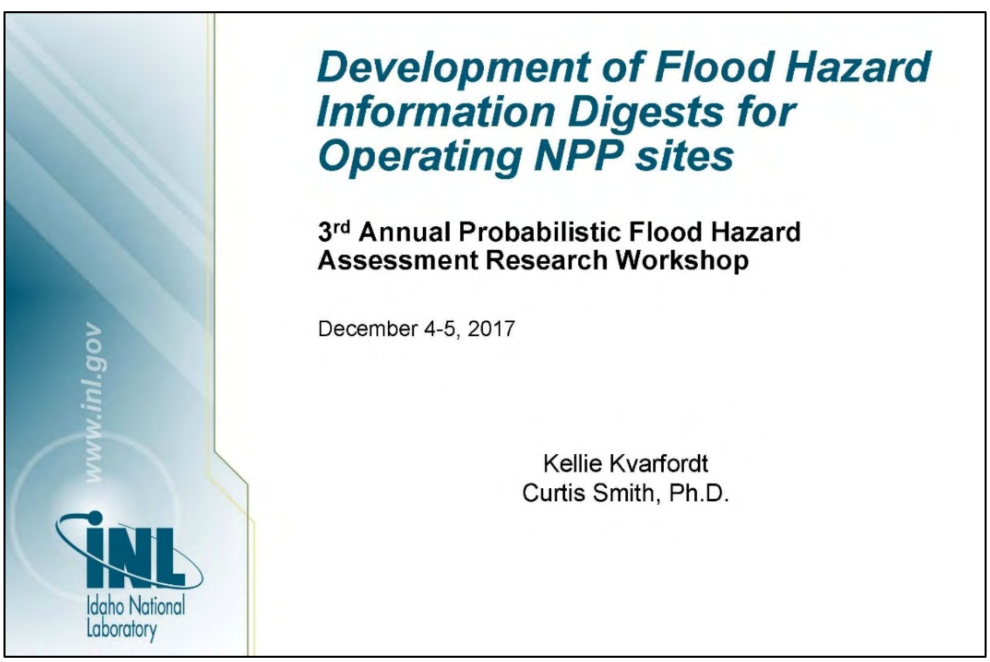
A particular challenge in developing probabilistic external hazard estimates within the SDP is that the required external hazard information is not readily accessible. It is challenging for NRC staff to assemble and analyze the information within the time available for the SDP. Thus, there is a need to better organize external hazard information at operating reactor sites and improve its accessibility for NRC staff performing SDP analyses. The EHID application has been developed to address these needs.

Major flood related data sources that have been identified for reference in EHID include data from Fukushima NTTF Recommendation 2.1 and 2.3, precipitation frequency information from NOAA , flood frequency information from USGS, hurricane landfall/intensity information, as well as flood protection and mitigation strategies from NUREGs, FSARs, IPEEE submittals, and SDP analyses. Additional data sources are being identified for other external hazard inclusion. In addition to providing access to these and other data sources, the information digest can provide, where needed, guidance for using the available information.

The EHID has been implemented as a cloud-based web application. The digest utilizes the INL's Safety Portal, a system that helps integrate and manage a comprehensive collection of many different kinds of content including web pages, web applications, models, and documents where users may store, use, share, modify, or otherwise contribute to projects. The information digest shares available services such as user account management, file sharing, and a publications/ permissions/ subscriptions model.

Because the database contains a mixture of publicly and non-publicly available information, the EHID application is available only to NRC staff and contractors with appropriate authorization. Within the application access to individual items is controlled by those authoring the information. Initial data population efforts for flooding are nearing completion, and other external hazard data source identification and population efforts are commencing. The bulk of data population is targeted for completion by the end of June 2018. Maintenance will be folded into other ongoing data related activities performed by INL on behalf of the NRC.

3.3.4.3.2 Presentation



Project Overview

- Organize flooding information and build database of currently available site-specific flood hazard information to
  - Support development of a risk-informed analytical approach for flood hazards
  - Help Senior Reactor Analysts (SRAs) develop simple flooding models and reasonable hazard curves that fit into SAPHIRE modeling world

…in order to
  - Develop regulatory tools and guidance for NRC staff with regard to probabilistic flood hazard assessment (PFHA) for nuclear facilities
  - Support risk-informed reactor oversight activities such as evaluating the risk-significance of inspection findings

- **Expand the digests to include other natural external hazard information**

2

Status

- **Completed**
  - Flooding Hazard Information Needs Workshop
  - Reviewed existing NRC databases
  - Designed and implemented beta of flood hazard information database
  - Beta testing/demonstrations
  - Majority of key flood related data sources have been populated
- **Remaining**
  - Post Fukushima flooding reevaluation information
  - Expansion to other natural external hazards
  - User Guide Updates

3

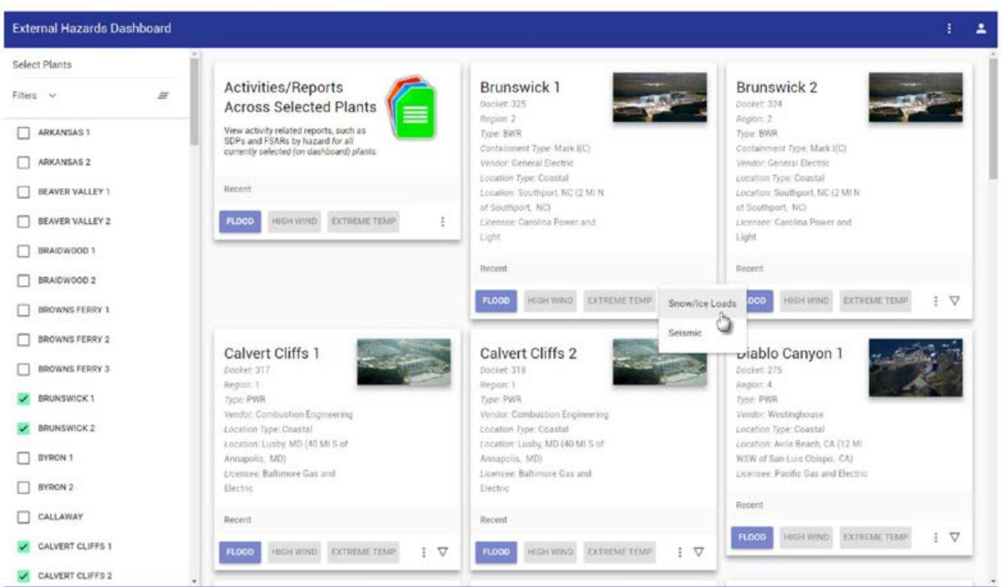
Idaho National Laboratory

External Hazards Web Application

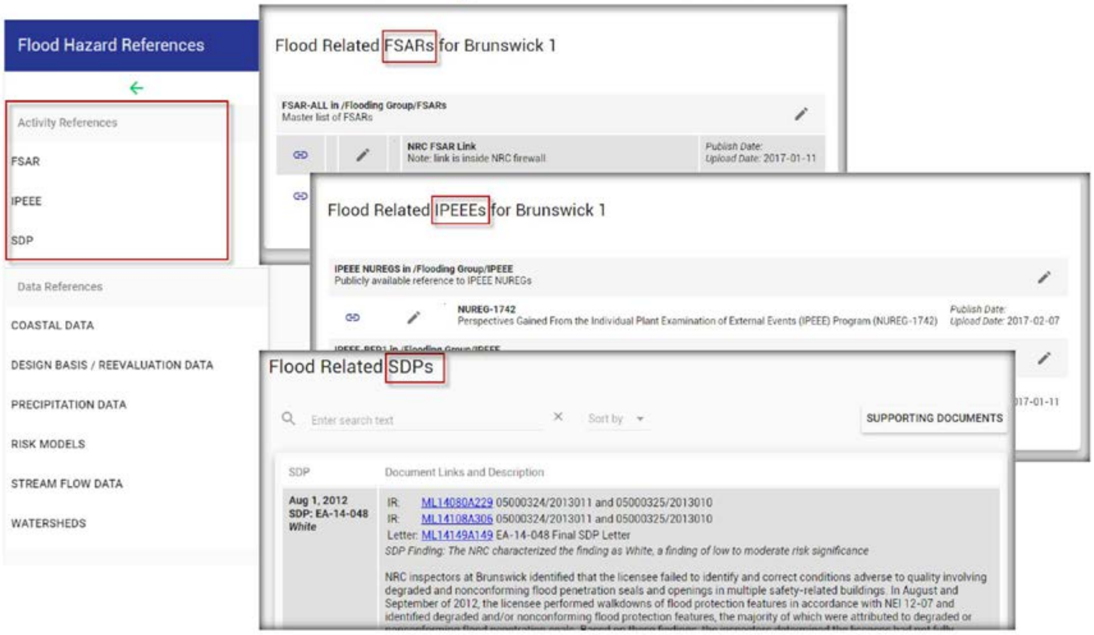
*Available only to authorized NRC staff and contractors

Idaho National Laboratory

External Hazards Dashboard



Drill-down to Plant Specific Activities…



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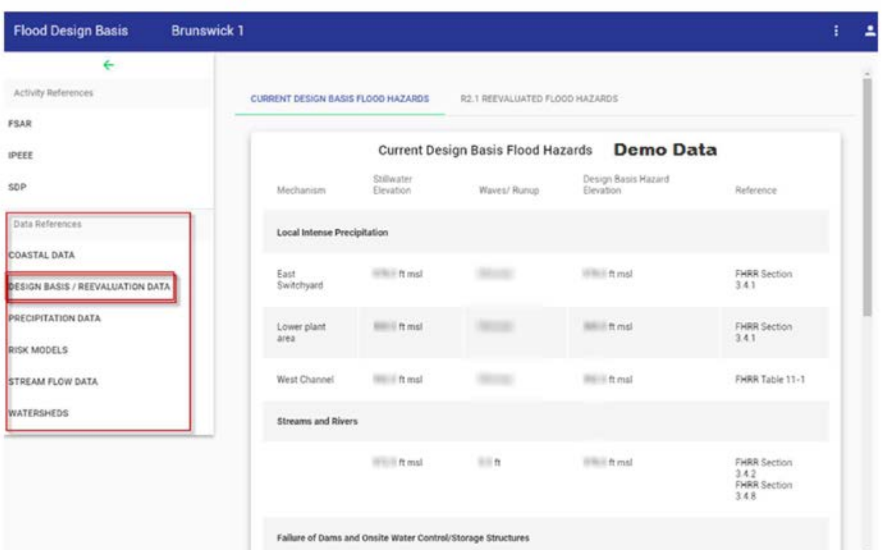
…and Plant Specific Data Sources



Sources: NRR's Mitigating Strategies Flood Hazard Information Database and Army Corp of Engineers (ACE)

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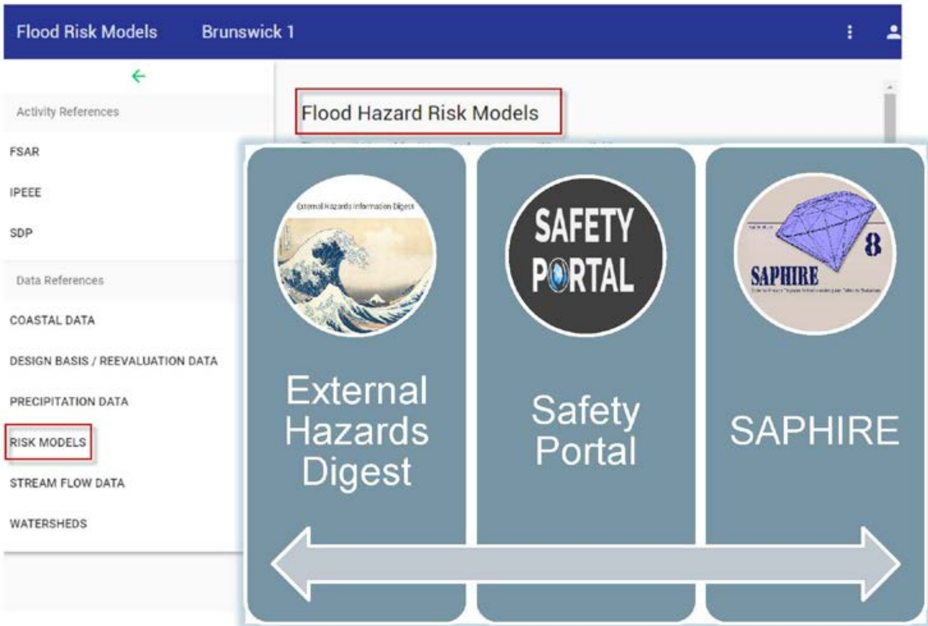
Risk Models



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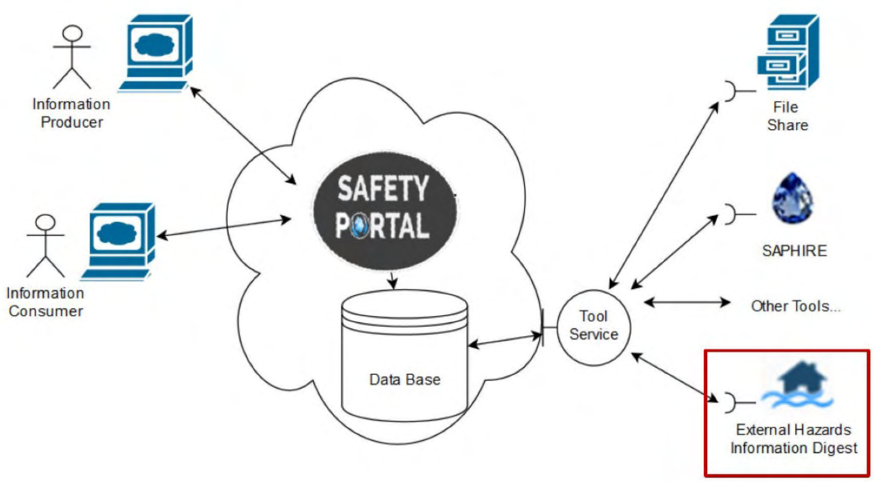
Integration with Safety Portal



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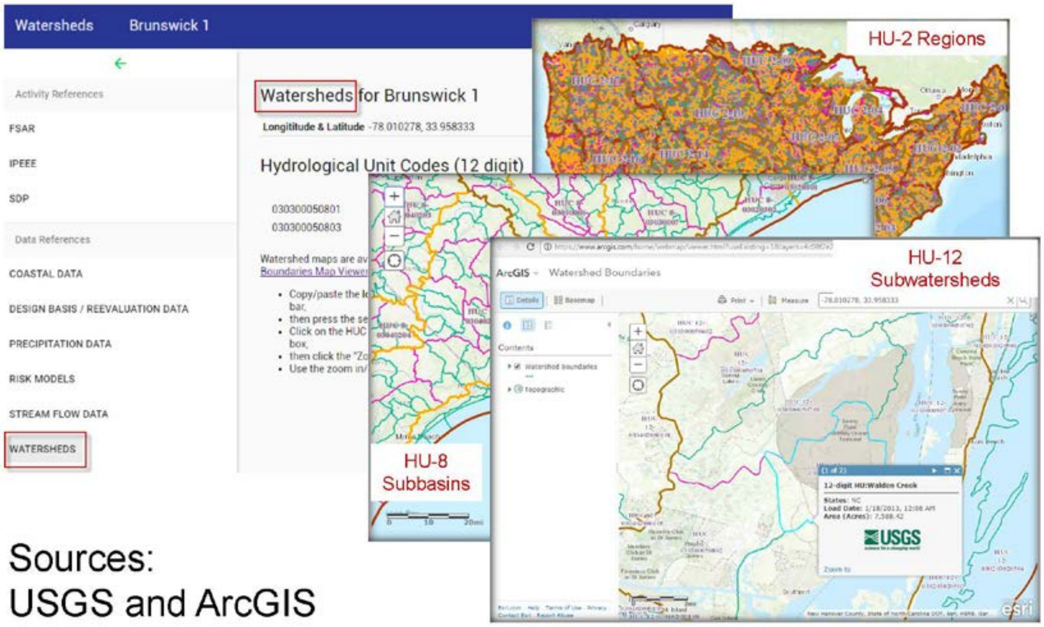
Idaho National Laboratory

Watershed Data



Sources:
USGS and ArcGIS

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Idaho National Laboratory

Precipitation Data

Precipitation Data | Brunswick 1

Activity References
- FSAR
- IPEEE
- SDP

Data References
- COASTAL DATA
- DESIGN BASIS / REEVALUATION DATA
- PRECIPITATION DATA
- RISK MODELS
- STREAM FLOW DATA
- WATERSHEDS

Precipitation Data for Brunswick 1

Latitude & Longitude 33.958333, -78.010278

NOAA Atlas 14 Precipitation Data Downloads
Partial duration series (PDS) CSV file
Frequency annual maximum series (AMS) CSV file

NOAA Atlas 14 Database precipitation frequency information
The Precipitation Frequency Data Server (PFDS) is a point-and-click interface developed to deliver NOAA Atlas 14 precipitation frequency estimates and associated information. Enter the latitude and longitude of the plant to display its precipitation estimates.

Current NWS Probable Maximum Precipitation (PMP) Documents
Index of Hydrometeorological regional reports for Probable Maximum Precipitation (PMP) guidance and studies.

- HMR51 (1978) Probable Maximum Precipitation Estimates, United States East of the 105th Meridian
- HMR52 (1982) Application of Probable Maximum Precipitation Estimates - United States East of the 105th Meridian
- HMR53 (1980) Seasonal Variation of 10-Square-Mile Probable Maximum Precipitation Estimates, United States East of the 105th Meridian

Isopluvial plots for 100 year interval
NOAA Atlas 14 cartographic maps of precipitation frequency estimates for selected average recurrence intervals.
1 hour, 6 hour, 24 hour, 48 hour, 10 day, 30 day, 60 day

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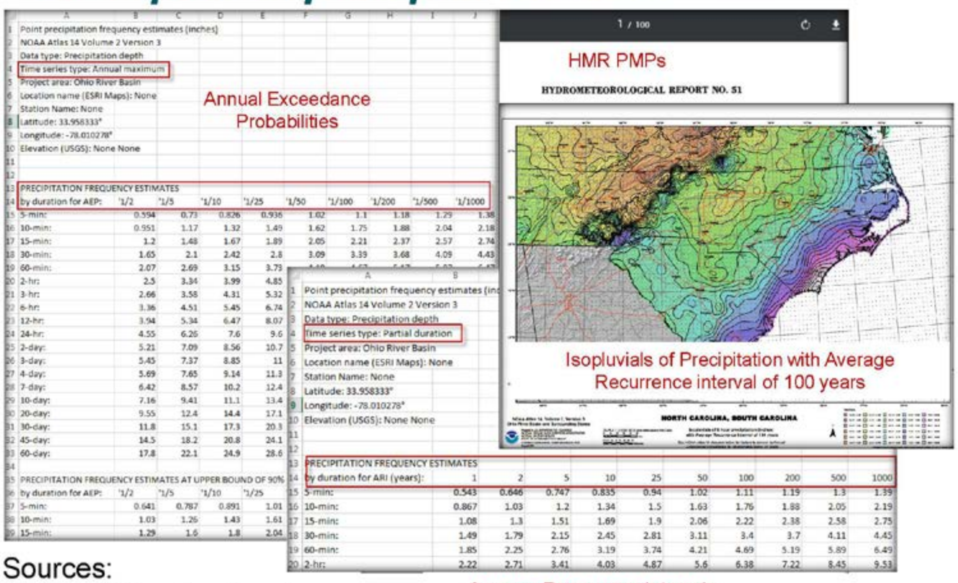
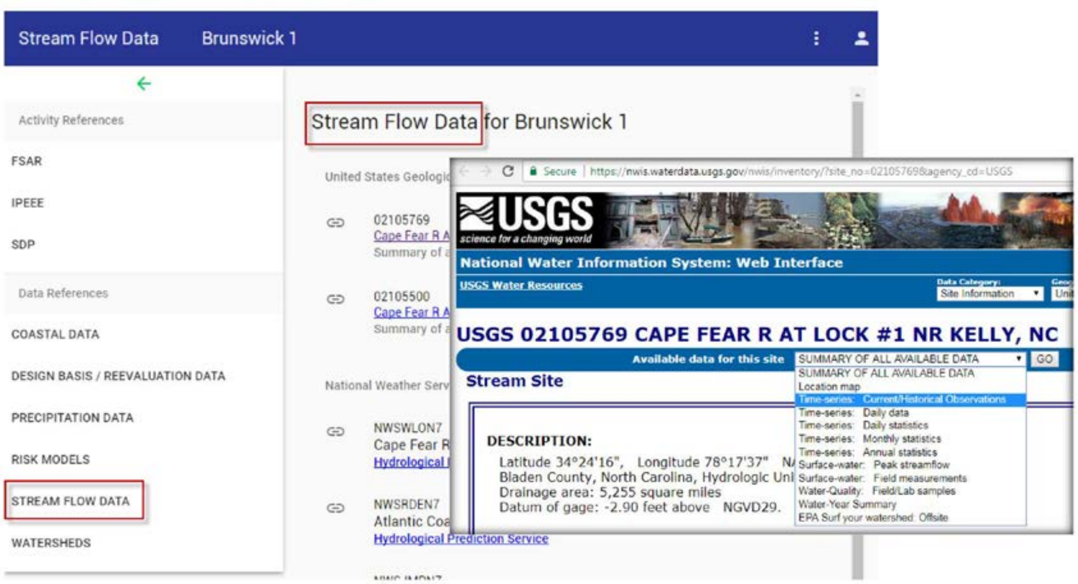
Examples of precipitation data



Average Recurrence Intervals

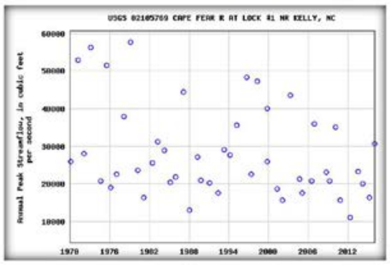
Sources:
National Weather Service
and NOAA Atlas 14

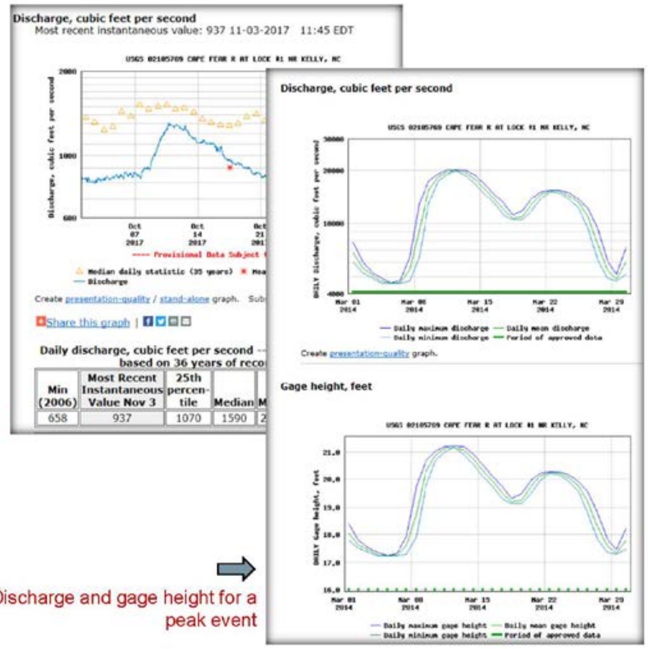
Stream Flow Data



Examples of stream flow data

Annual maximum series of peak flow





Discharge data in the past seven days, available in 15 minute detailed increments

Discharge and gage height for a peak event

Source: USGS

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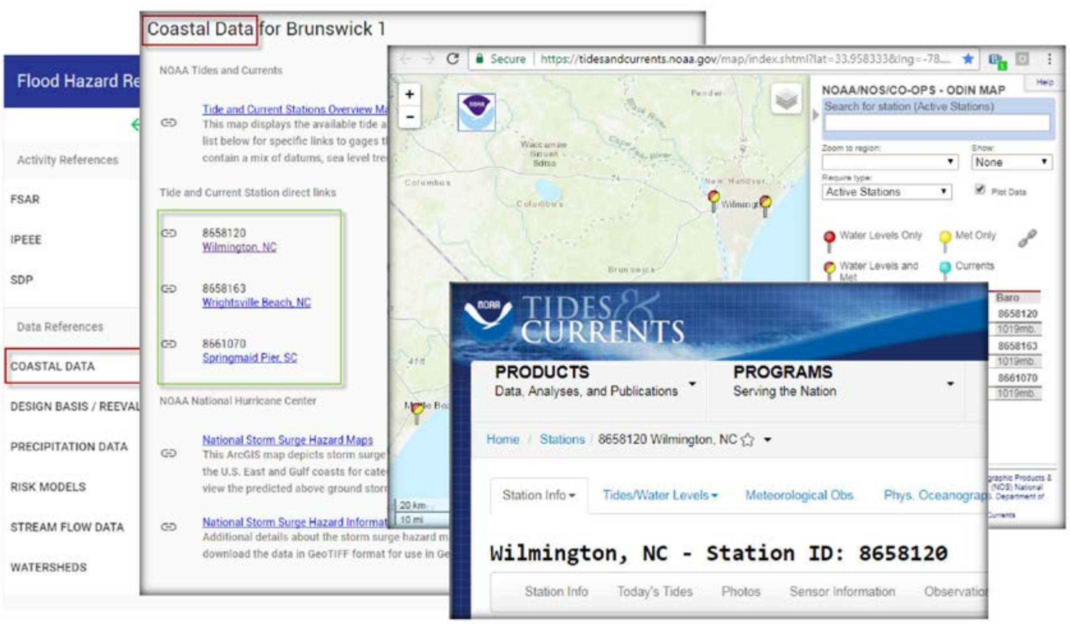
Coastal and Great Lakes Data



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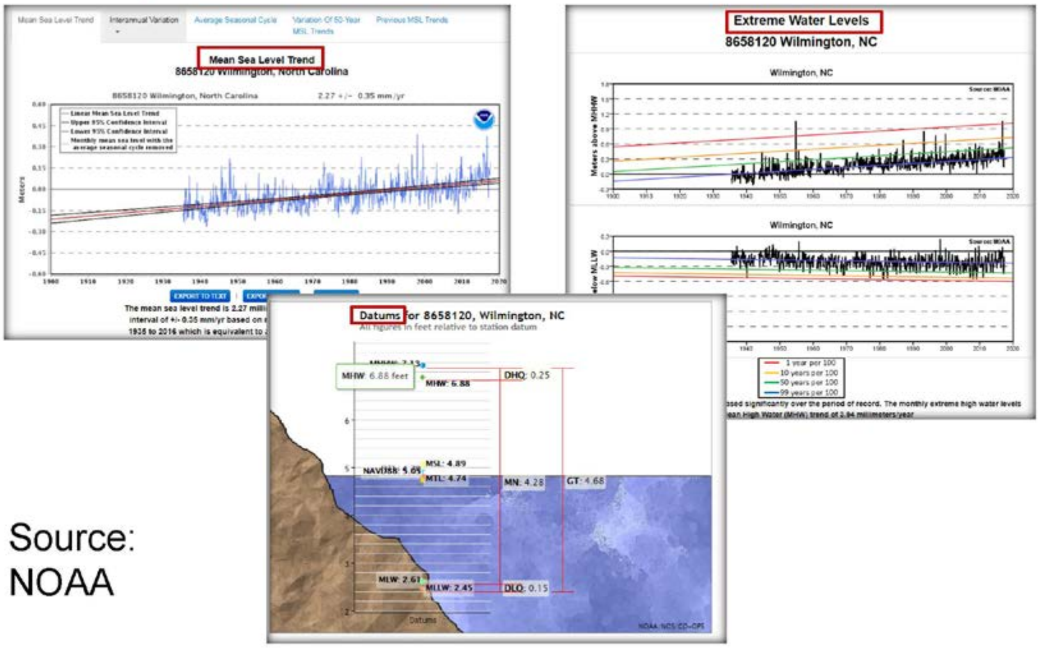
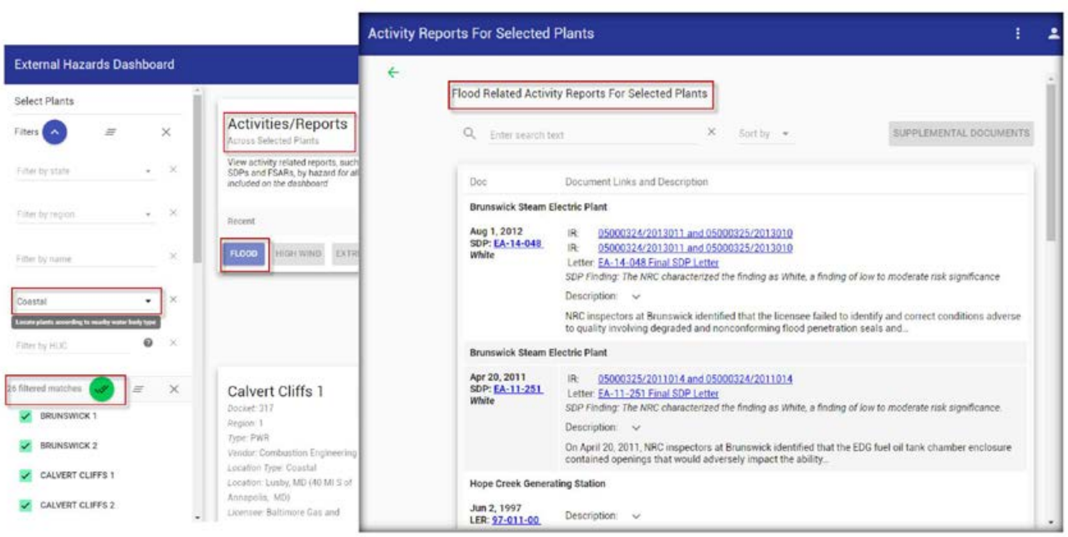
Examples of coastal data



Source:
NOAA

Activity/Report Drill Down Across Plants



Expansion to Other Natural External Hazards

- The work on other natural hazards is in progress and is being coordinated with the NRC External Hazards Center of Expertise (EHCOE)
- High winds
  - Tornado
  - Hurricane
- Extreme temperatures/humidity
  - High and low temperature extremes
  - Wet-bulb temperature
- Snow/Ice loads
- Seismic

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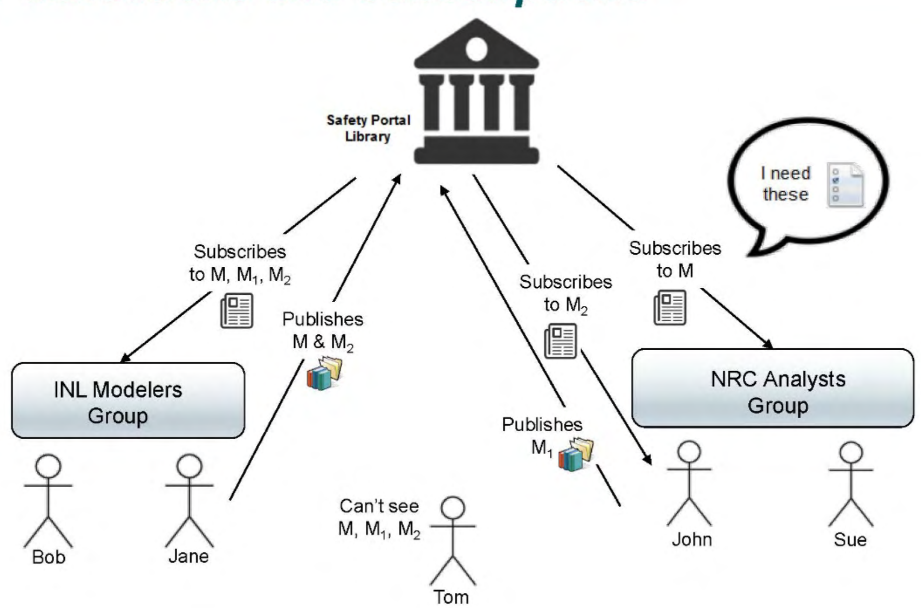
Publications and Subscriptions



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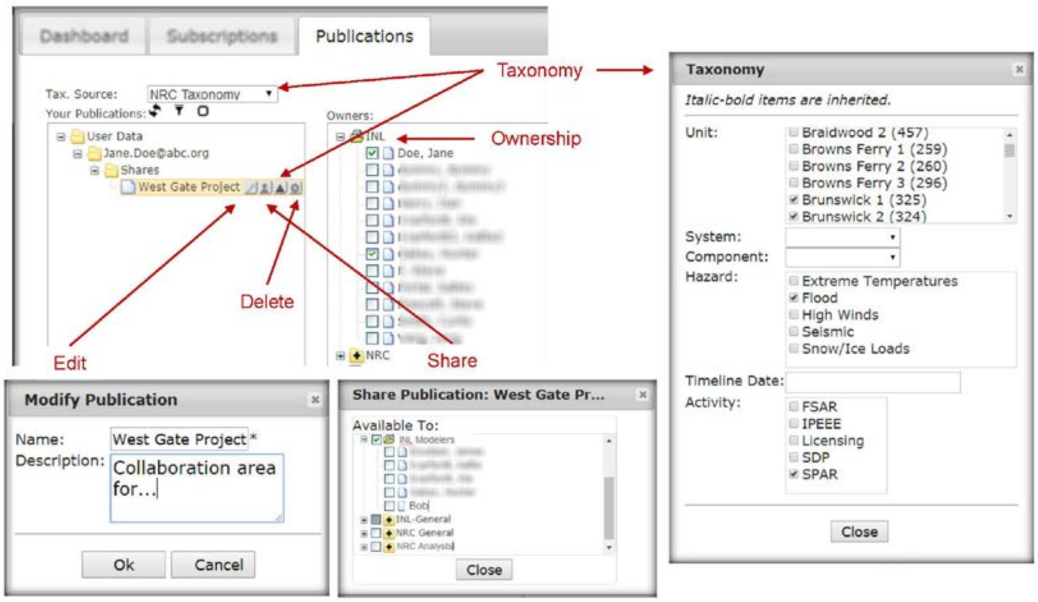
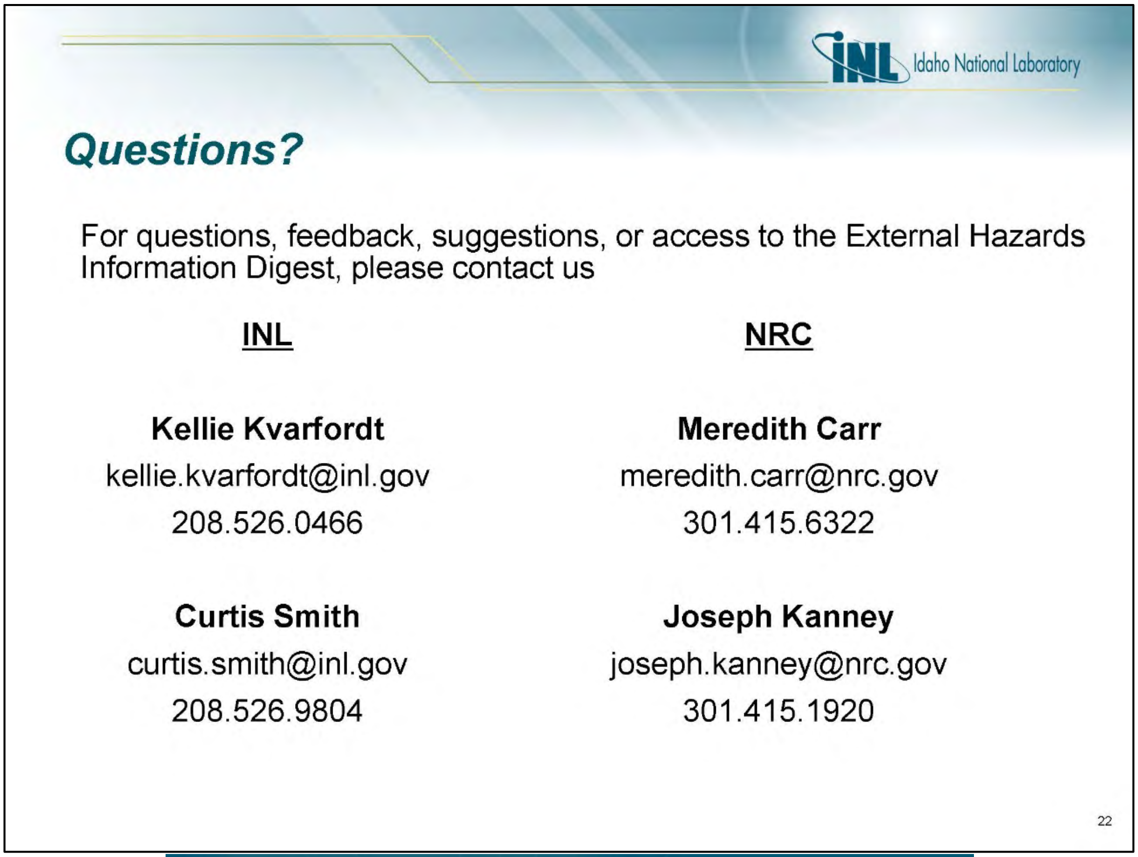
Anatomy of a Publication



Summary

- Flood Hazard Information Digest is being adapted to be a more broadly defined External Hazards Information Digest
- The External Hazards Information Digest organizes and presents a variety of relevant, plant specific information
  - This mix of publicly and non-publicly available information is available to select NRC staff
  - Also available to contractors with appropriate authorization
  - Access to individual items is controlled by those authoring the information
- Major flood hazard data sources have been identified and most are currently available in the digest
- Additional natural external hazard data sources are being identified for inclusion to the digest during FY18



3.3.4.3.3 Questions and Answers

Question:

So, I'm curious since I know you said a lot of the information is publicly available…if a licensee has a reason to assess these things as much as the NRC. Say there's a significant determination process and they would like to simplify their research as well… is there any mechanism that they can ask the NRC, "Can you give us all the links to publicly available information? Since you have it very readily available?"

Response:

They would go through the NRC to determine whether that was appropriate or not. I guess the licensing office would make that determination... not us here in research. So, if the licensing office wanted to make that available to the licensees and that was an appropriate thing to do, then I don't think there would be any problem with it. But that wouldn't be a decision that research makes.

Question:

Thank you very much Kelly. One thing I kept thinking about as you went through different data sets… I'm very curious… do you have the pedigree of the data? Do you have information on the QA/QC? What was done at the time of the collection of the data and how you could determine how the data was collected… who collected it? Under what procedures they collected it? Do you have that information?

Response:

I really don't. These are from external agencies and that is their mission to collect that data. I guess we could probably provide links into any background that they had on that but we're not personally validating that data. I know that the specific stuff that we make available: the stations and the gauges, hydrologists have cross-checked each other to make sure that we're providing the correct links… the things that we have control over.

Question: It's a kind of a curiosity question I guess. Do you have flood forecasts locations… say upstream of the power plants included in the database? And also, upstream dams?

Response:

We don't have the upstream dams right now but that is certainly under consideration as part of some of the other external hazard sources. We're evaluating what sort of information we want to put in there regarding upstream dams, as you're well aware, some information about upstream dams is information that we may have obtained from other agencies, so we would have to consult with the other agencies to make sure that we're not providing information that shouldn't be provided to people who don't need. On the same pages as the USGS gauge sites, there's links to the upstream and downstream forecasting sites…they've been identified, I'm not sure if they have been worked into the database - but those flood forecast sites are pretty short in history and I don't know if our turnover is that fast for looking at forecasts.

Question:

A couple of other previous speakers were focusing on other extremes. Have you had the opportunity to include climate projection information in the database? Specifically, precipitation stream flows that have been down scaled or other sources such as those?

Response:

No.

3.3.5 Day 1: Session 1E - Paleoflood Studies

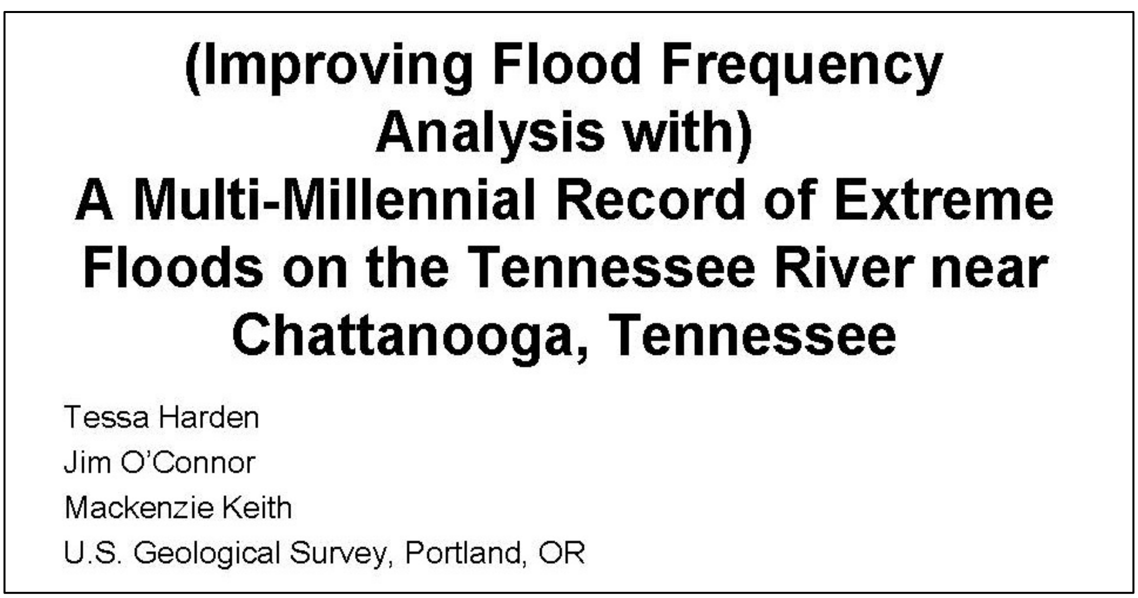
Session Chair: Mark Fuhrmann, NRC/RES/DRA/FXHAB

3.3.5.1 Improving Flood Frequency Analysis with a Multi-Millennial Record of Extreme Floods on the Tennessee River near Chattanooga, Tessa Harden*, Ph.D., Jim O'Connor, Ph.D. and Mackenzie Keith, U.S. Geological Survey (Session 1E-1; ADAMS Accession No. ML17355A093)

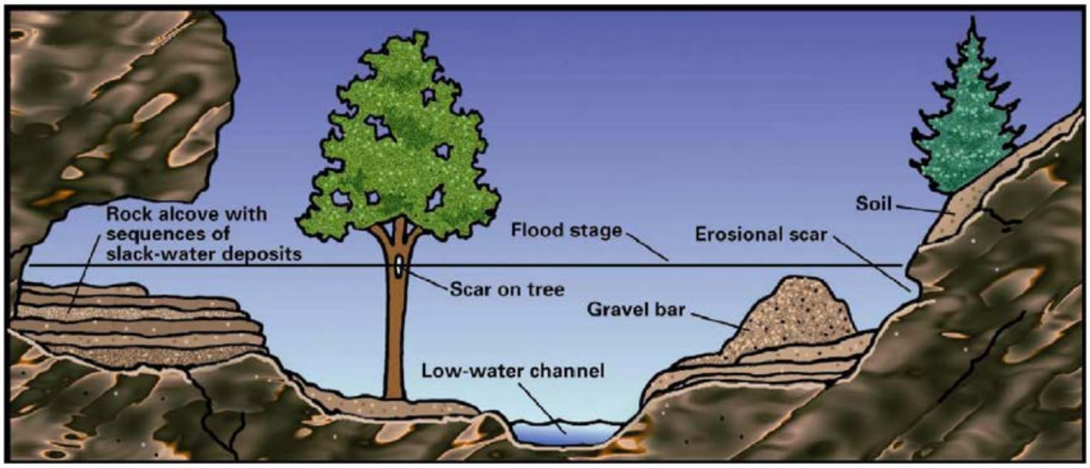
3.3.5.1.1 Abstract

A rich history of large late-Holocene Tennessee River floods is preserved in caves and alcoves throughout the Tennessee River Gorge area near Chattanooga, Tennessee. Preliminary stratigraphic analyses, coupled with geochronologic techniques, show evidence of at least four floods occurring in the last ~3,000 years with possible discharge estimates greater than or similar to the 1867 peak of record (460,000 ft3/s at Chattanooga, Tennessee). One of those floods may have occurred in the last 400 years and has an estimated discharge at least twice the magnitude of the 1867 flood. At least 1–2 additional large floods with estimated peaks similar to the 1917 flood (341,000 ft3/s) occurred in the last ~3,000 years. In addition to flood evidence found in caves and alcoves, flood deposits in exposed stratigraphy at Williams Island, an alluvial island at the head of the gorge, date to ~9,000 years. Determining accurate discharge estimates in this section of the river is difficult due to the backwater from the gorge constriction during high flows, but the flood records preserved here can be used to validate flood evidence downstream in the gorge, where the stable boundary and narrow valley provide more reliable discharge estimates. Stratigraphic records of past floods to reduce uncertainty in flood frequency analyses have been used extensively in the arid western United States, especially for floods with low annual exceedance probabilities. Preliminary results indicate that previously developed techniques to develop stratigraphic records of past floods can be successfully applied to reduce uncertainty in flood frequency analyses in the temperate eastern regions of the United States.

3.3.5.1.2 Presentation

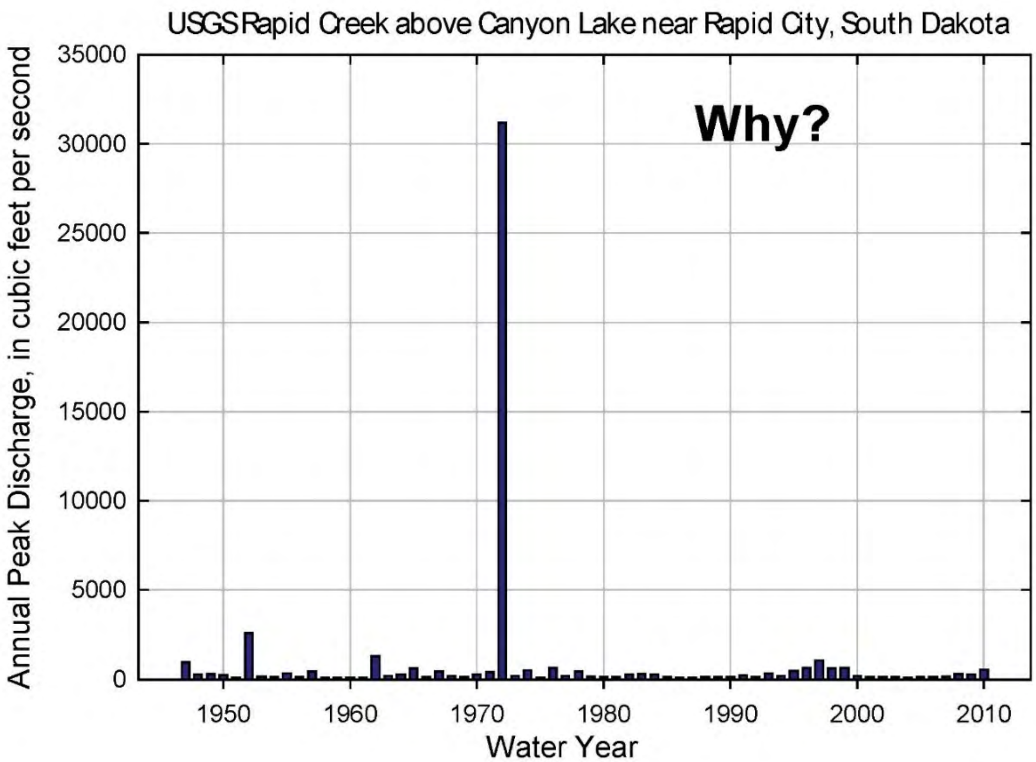


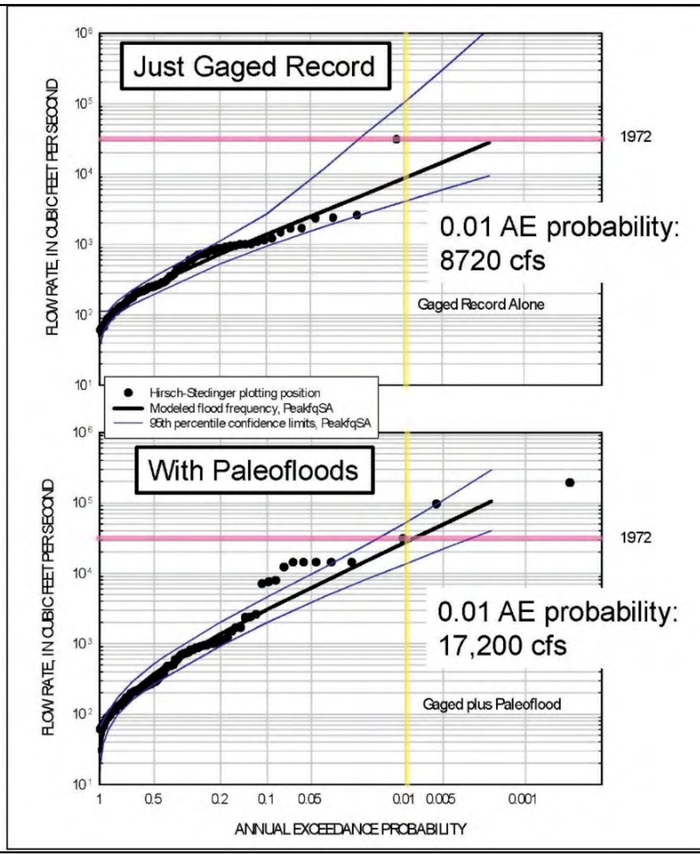
What is "Paleoflood" Hydrology



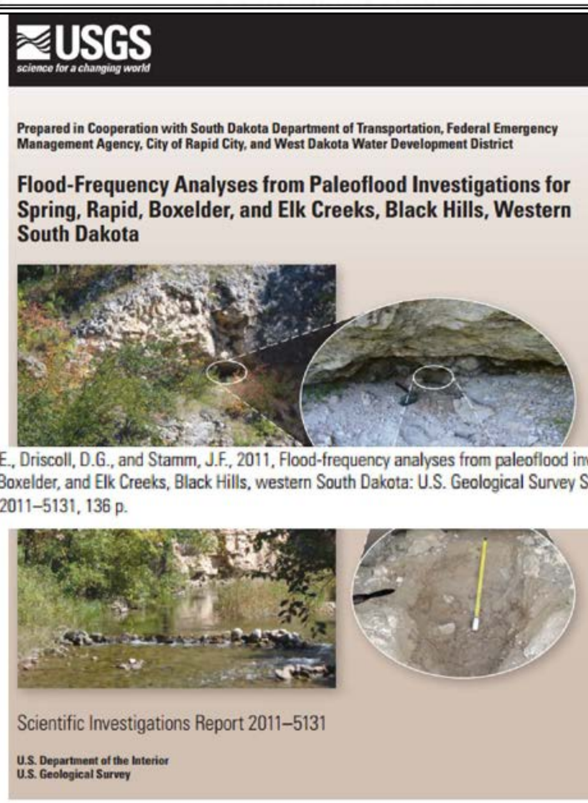
....using geologic evidence to understand flood history...

USGS



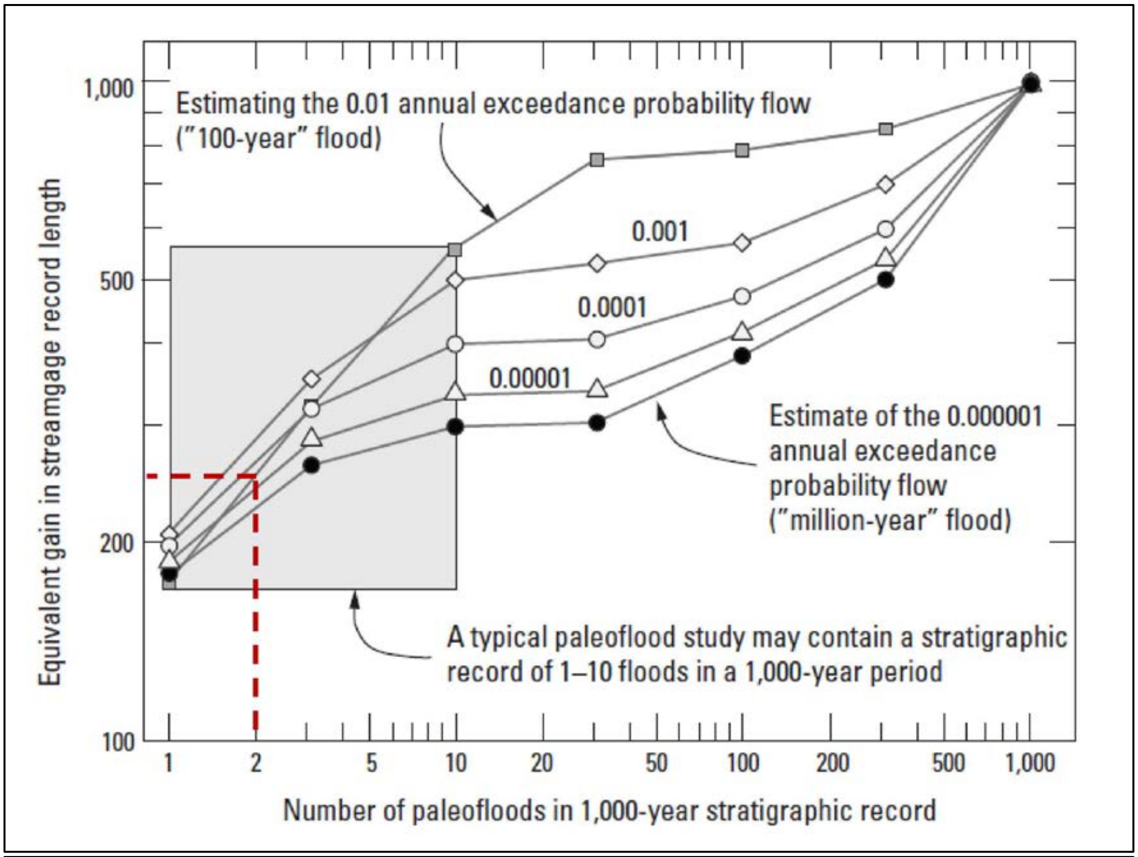


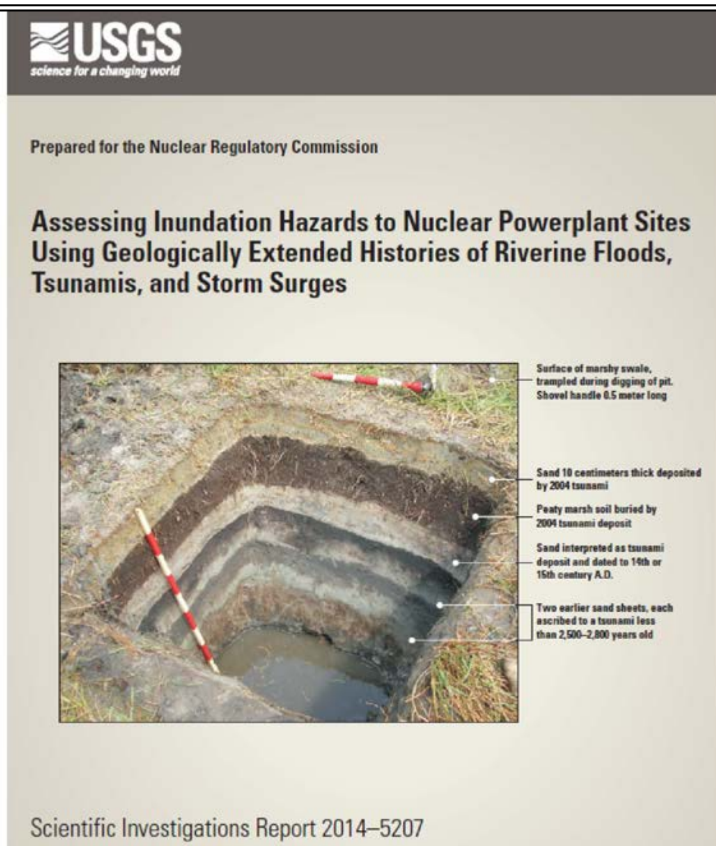
USGS

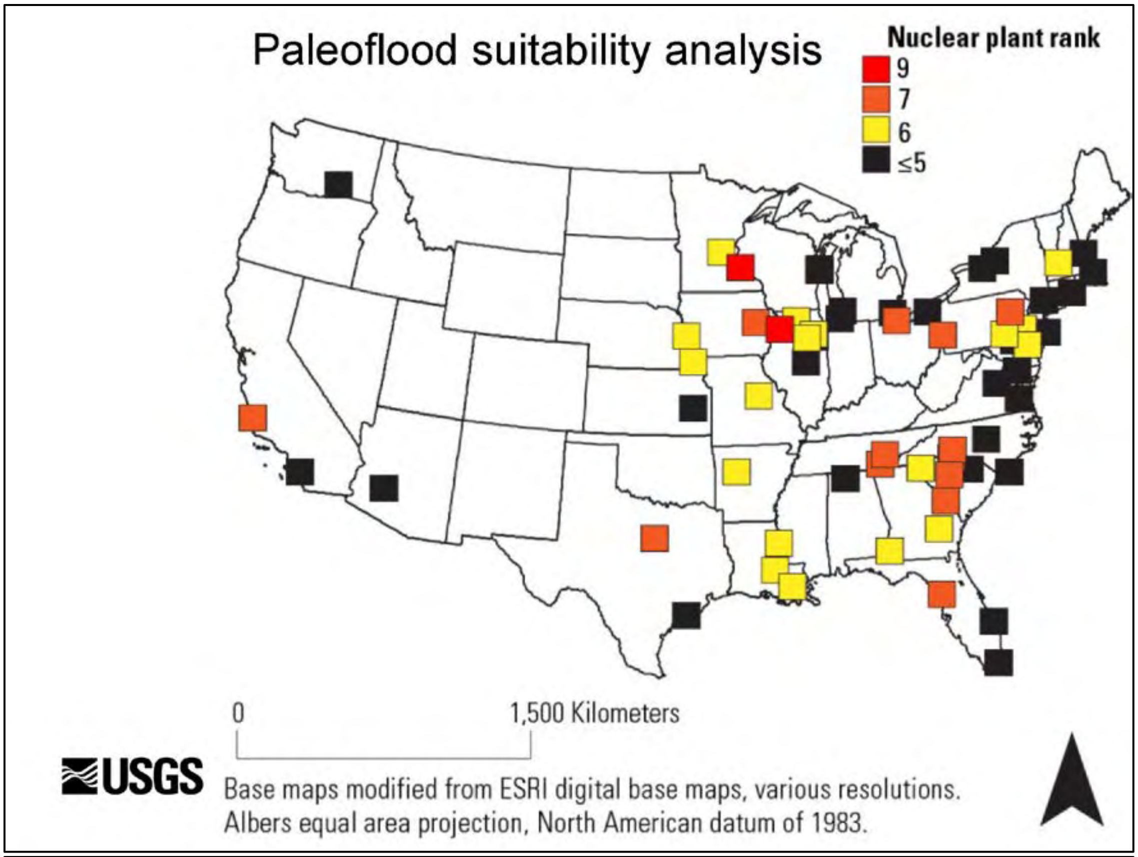


Harden, T.M., O'Connor, J.E., Driscoll, D.G., and Stamm, J.F., 2011, Flood-frequency analyses from paleoflood investigations for Spring, Rapid, Boxelder, and Elk Creeks, Black Hills, western South Dakota: U.S. Geological Survey Scientific Investigations Report 2011–5131, 136 p.

USGS


Estimating the 0.01 annual exceedance probability flow ("100-year" flood)
0.001
0.0001
0.00001
Estimate of the 0.000001 annual exceedance probability flow ("million-year" flood)
A typical paleoflood study may contain a stratigraphic record of 1–10 floods in a 1,000-year period
Equivalent gain in streamgage record length
100
200
500
1,000
1
2
5
10
20
50
100
200
500
1,000
Number of paleofloods in 1,000-year stratigraphic record


USGS
science for a changing world
Prepared for the Nuclear Regulatory Commission
Assessing Inundation Hazards to Nuclear Powerplant Sites Using Geologically Extended Histories of Riverine Floods, Tsunamis, and Storm Surges
Surface of marshy swale, trampled during digging of pit. Shovel handle 0.5 meter long
Sand 10 centimeters thick deposited by 2004 tsunami
Peaty marsh soil buried by 2004 tsunami deposit
Sand interpreted as tsunami deposit and dated to 14th or 15th century A.D.
Two earlier sand sheets, each ascribed to a tsunami less than 2,500–2,800 years old
Scientific Investigations Report 2014–5207



Screening results:

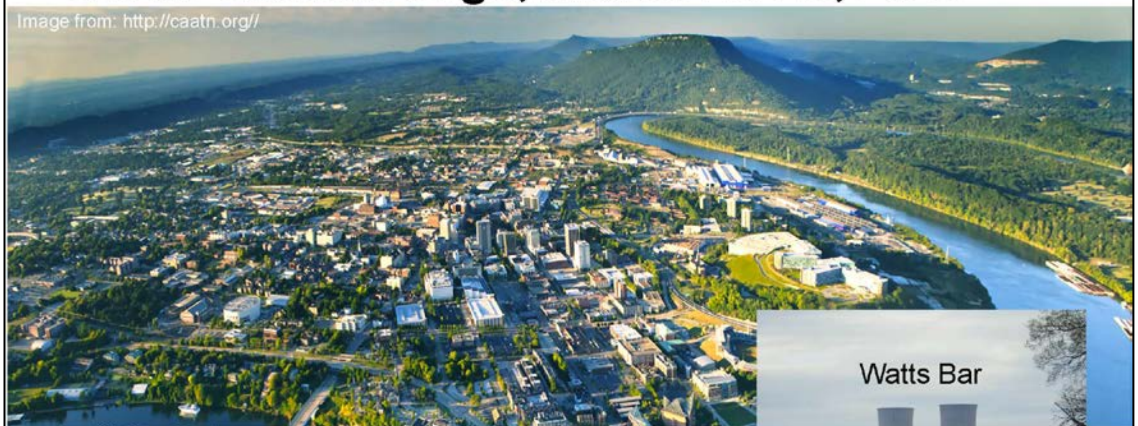
•Several southeastern US sites are potentially suitable, including several rivers with multiple sites.

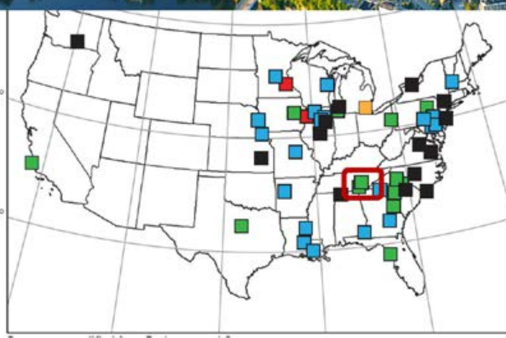
These include Susquehanna River, Pennsylvania; Tennessee River, Tennessee; and Catawba River, South Carolina.

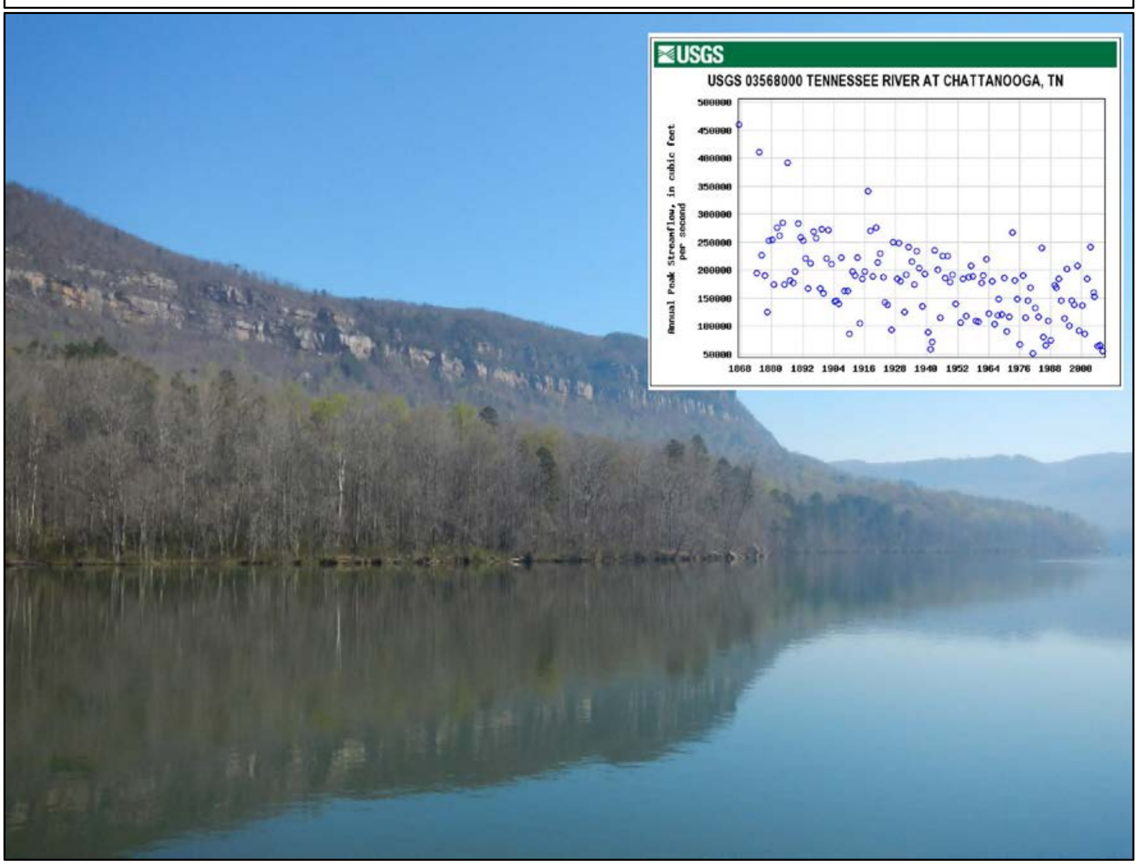
O'Connor, J.E., Atwater, B.F., Cohn, T.A., Cronin, T.M., Keith, M.K., Smith, C.G., and Mason, R.R., 2014, Assessing inundation hazards to nuclear powerplant sites using geologically extended histories of riverine floods, tsunamis, and storm surges: U.S. Geological Survey Scientific Investigations Report 2014–5207, 66 p., *http://dx.doi.org/10.3133/sir20145207*.

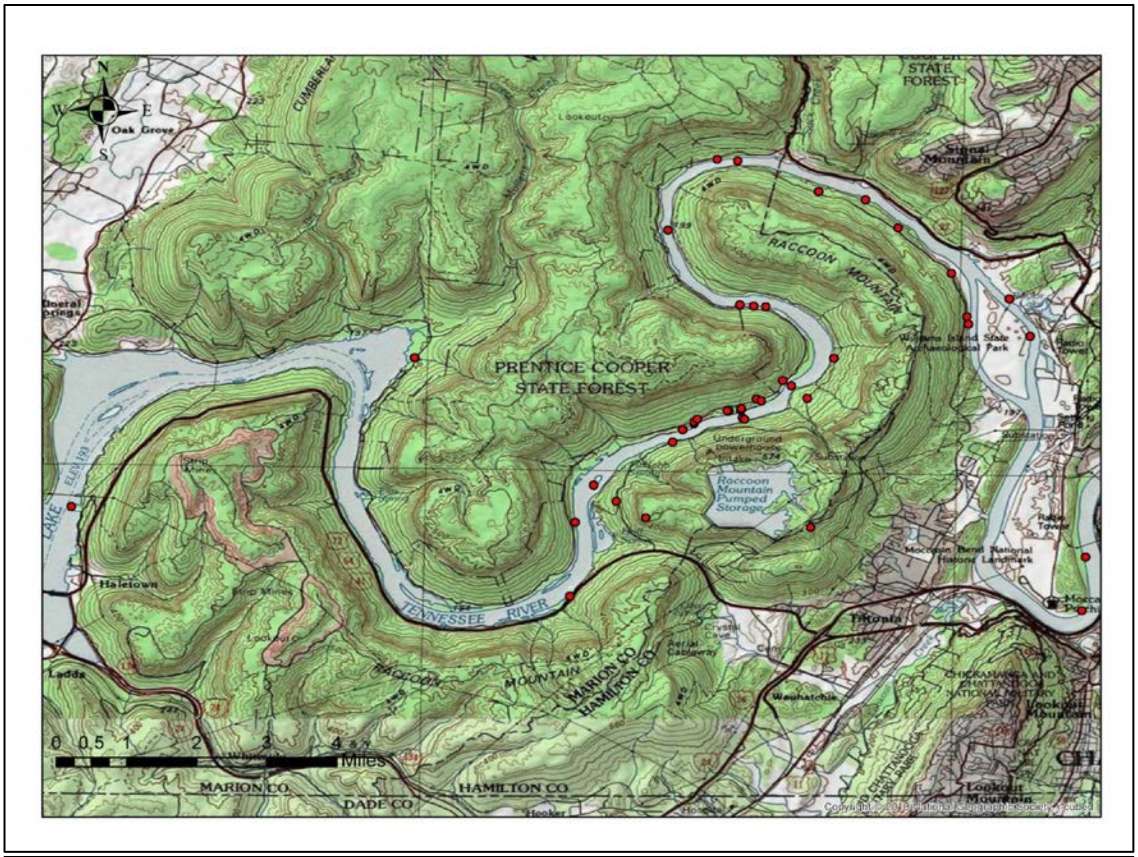
USGS

Off to Chattanooga, March 20-26, 2016

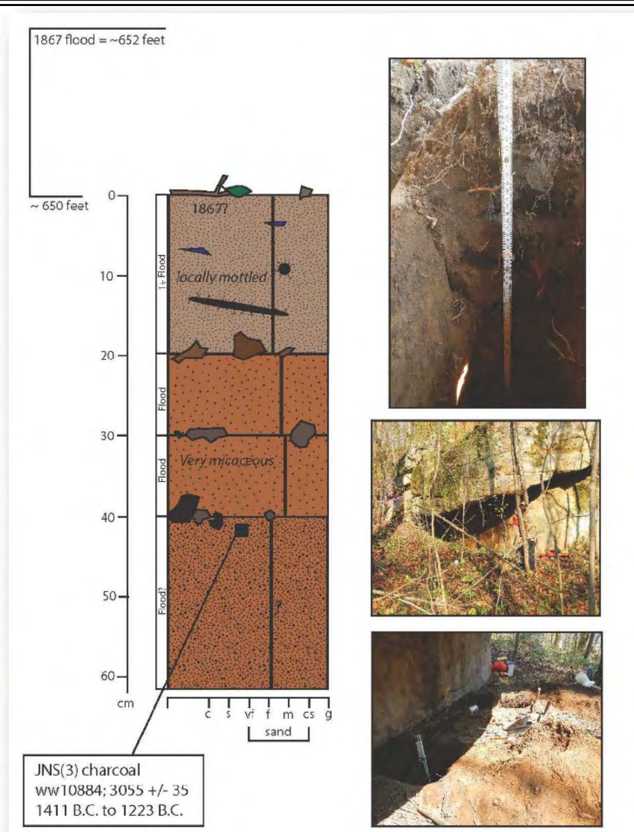


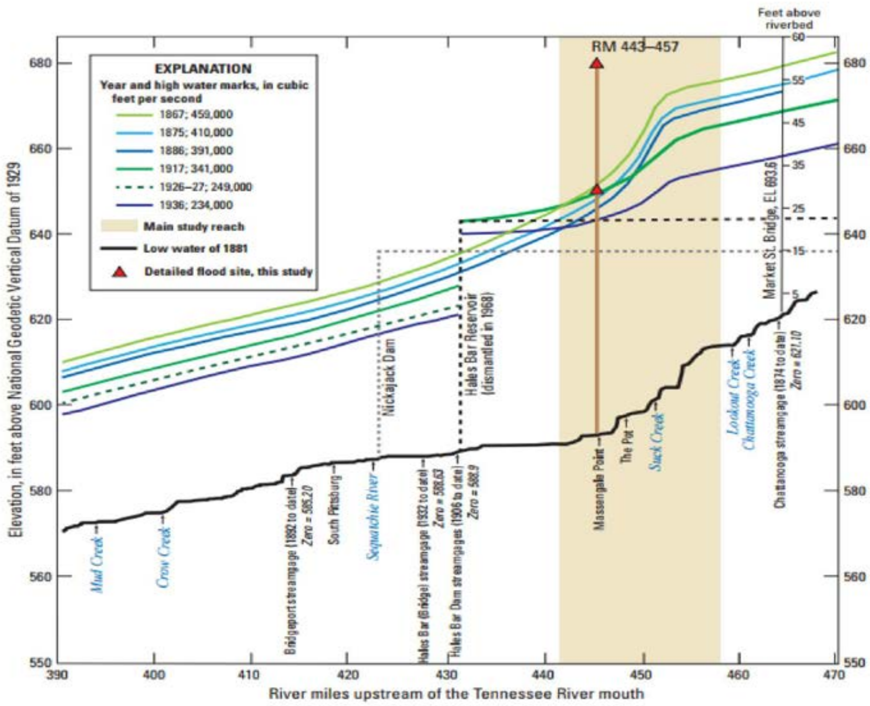




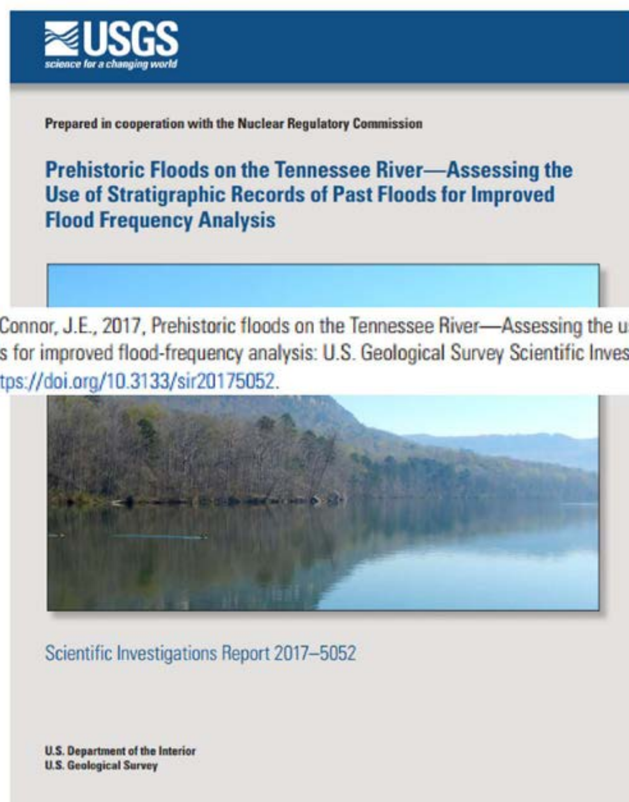

N
S
E
W
Oak Grove
PRENTICE COOPER
STATE FOREST
RACCOON MOUNTAIN
Raccoon
Mountain
Pumped
Storage
TENNESSEE RIVER
Haletown
RACCOON
MOUNTAIN
MARION CO
HAMILTON CO
DADE CO
0 0.5 1 2 3 4
Miles

"Jeff-n-Steph" site located in the Gorge at a similar elevation as the 1867 high water marks. This sites contains at least 3+ flood deposits in the last ~3,000 years.



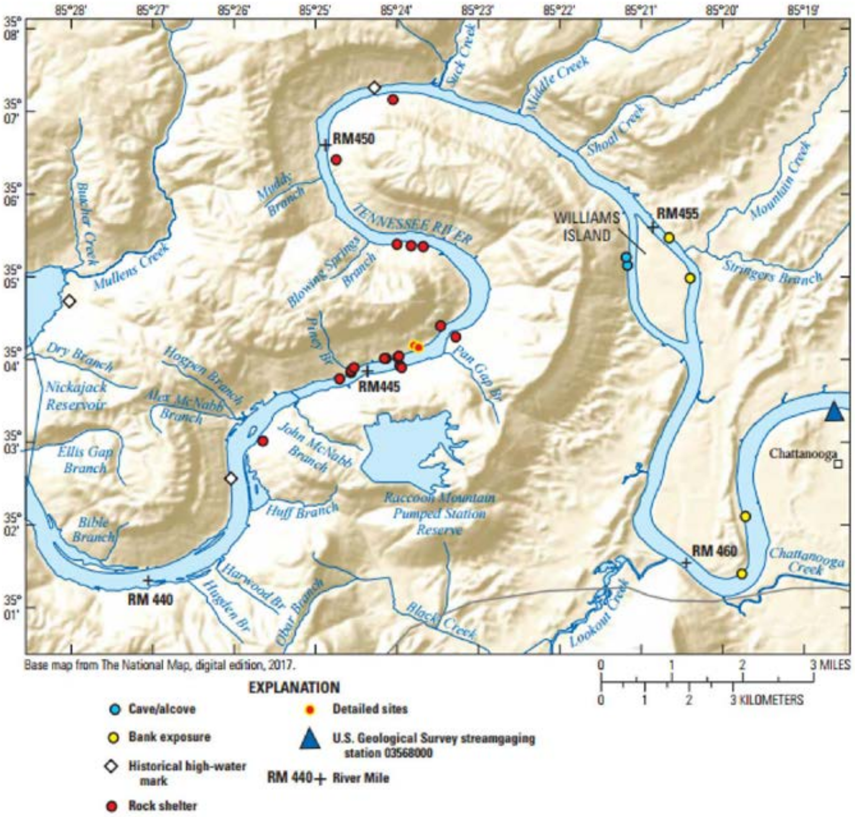


Modified from Tennessee Valley Authority, 1940

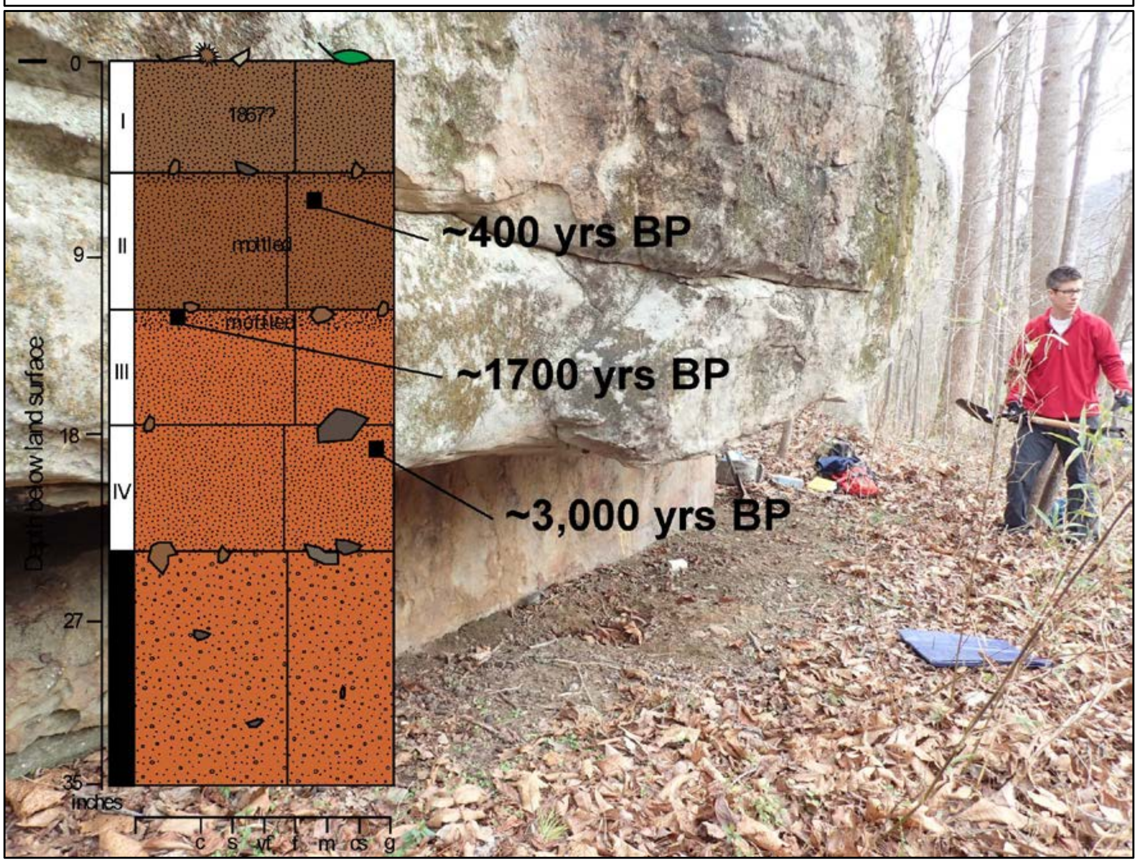


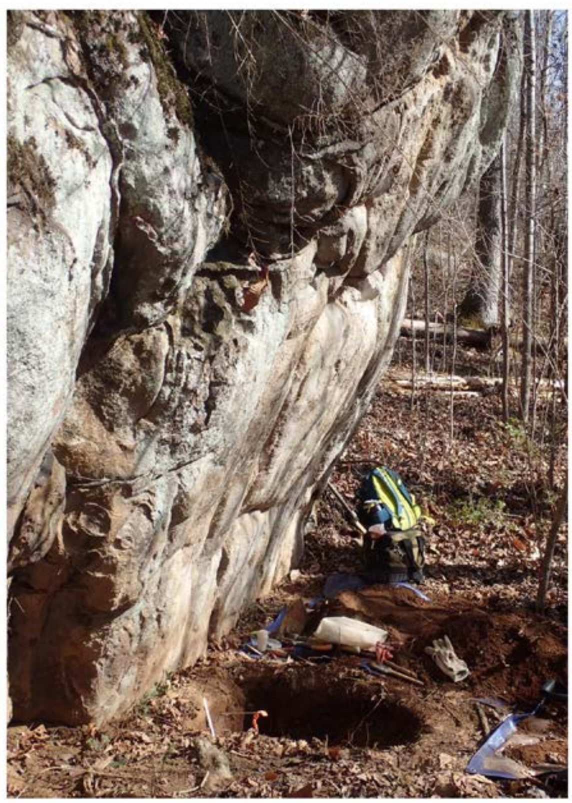
Harden, T.M., and O'Connor, J.E., 2017, Prehistoric floods on the Tennessee River—Assessing the use of stratigraphic records of past floods for improved flood-frequency analysis: U.S. Geological Survey Scientific Investigations Report 2017–5052, 15 p., https://doi.org/10.3133/sir20175052.

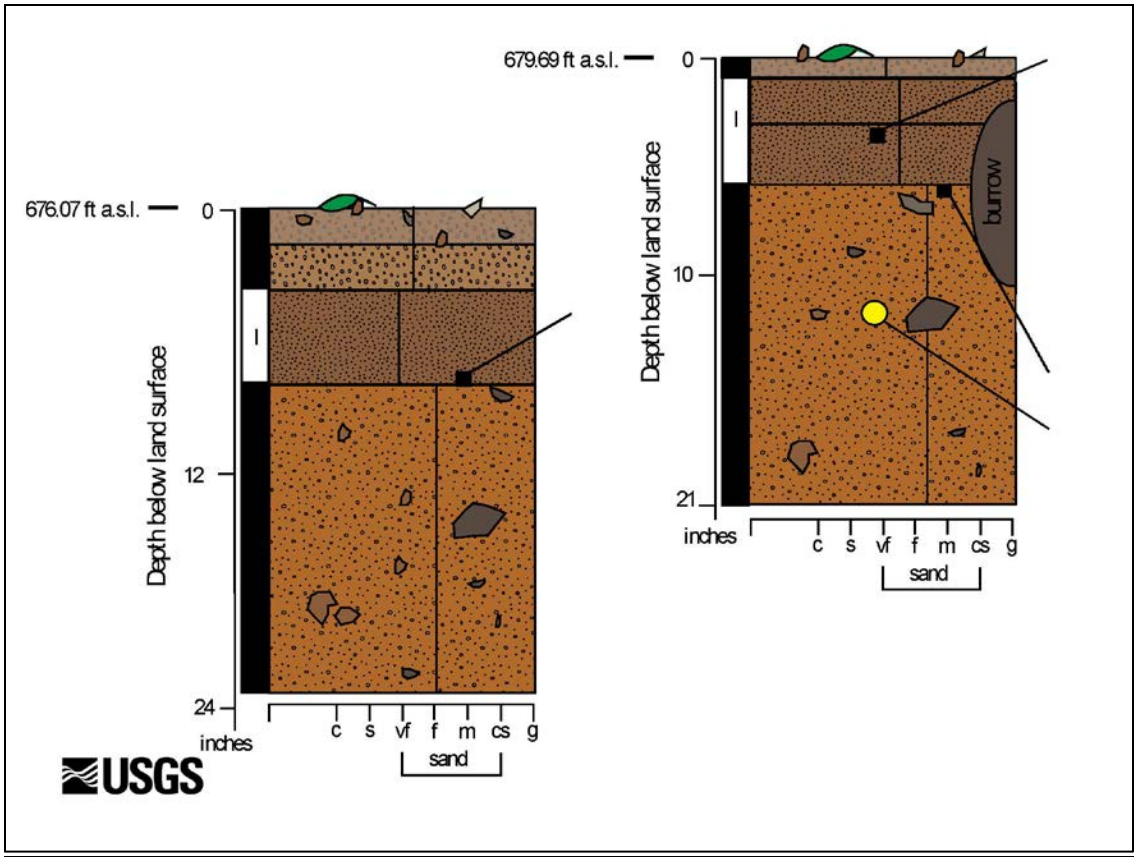
Fieldwork
February 2-9
2017

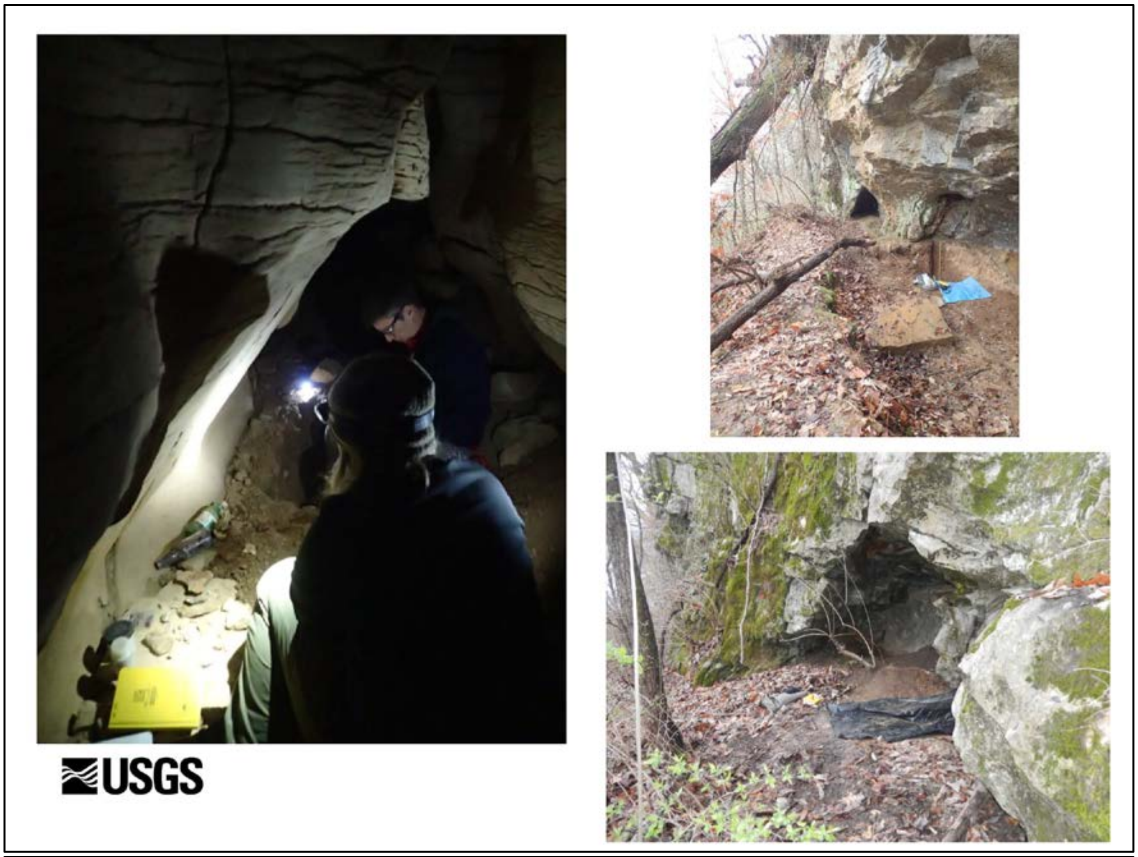


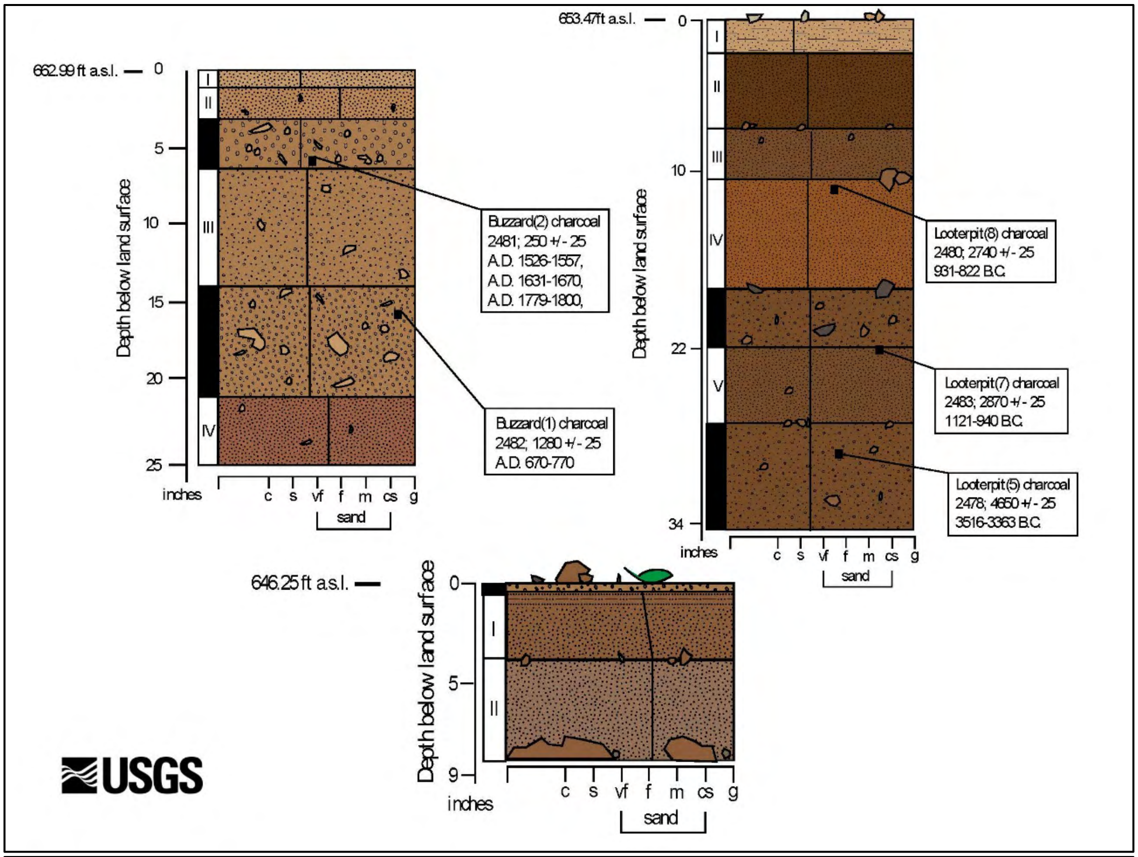
USGS

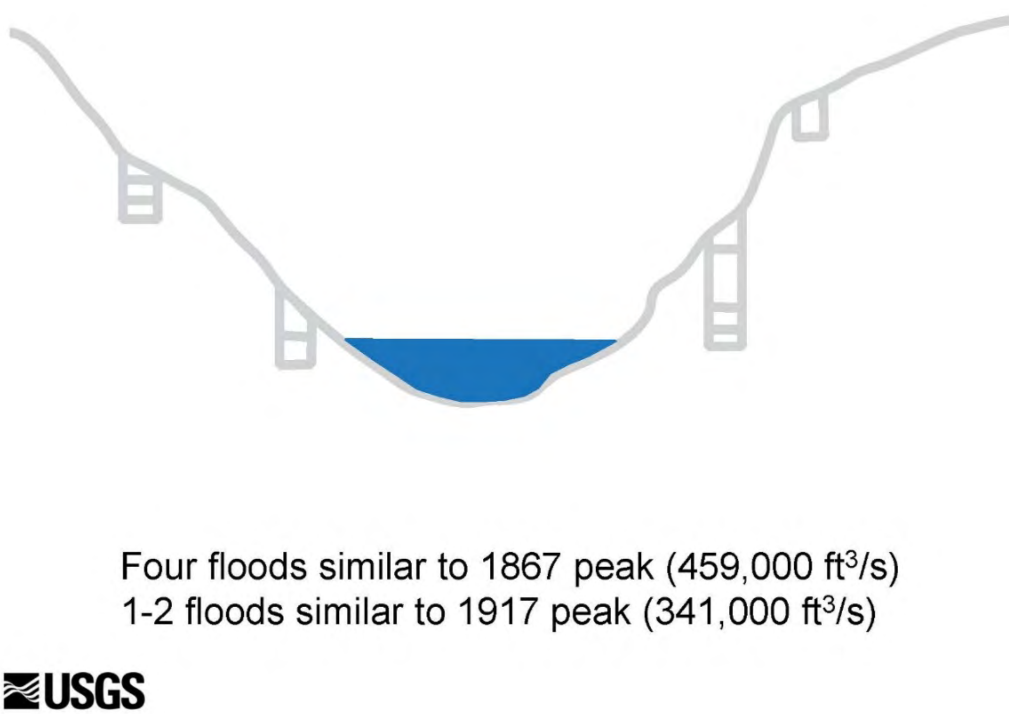





676.07 ft a.s.l.
0
12
24
inches
Depth below land surface
I
c
s
vf
f
m
cs
g
sand
USGS
679.69 ft a.s.l.
0
10
21
inches
Depth below land surface
I
burrow
c
s
vf
f
m
cs
g
sand


USGS





Four floods similar to 1867 peak (459,000 ft^3/s)
1-2 floods similar to 1917 peak (341,000 ft^3/s)

Still need to:

- Finish fieldwork (January-February 2018)
  - A few more alcoves
  - Stratigraphy at Williams Island
- Lab results
  - OSL
  - radiocarbon
- Hydraulic model
  - discharge magnitudes
- Flood Frequency Analysis

USGS

Funding and contact information:

- National Screening, and the Tennessee River scoping (2016) and implementation (2017-2019) funded by Nuclear Regulatory Commission, Office of Nuclear Regulatory Research

- USGS Personnel: Tessa Harden tharden@usgs.gov); Jim O'Connor (oconnor@usgs.gov); and Mackenzie Keith
- NRC Personnel: Mark Fuhrmann (mark.fuhrmann@nrc.gov); Meredith Carr (Meredith.Carr@nrc.gov); and Joseph Kanney (Joseph.Kanney@nrc.gov)

USGS

References:

- Harden, T.M., O'Connor, J.E., Driscoll, D.G., and Stamm, J.F., 2011, Flood-frequency analyses from paleoflood investigations for Spring, Rapid, Boxelder, and Elk Creeks, Black Hills, western South Dakota: U.S. Geological Survey Scientific Investigations Report 2011–5131, 136 p. http://pubs.usgs.gov/sir/2011/5131/
- Harden, T.M., and O'Connor, J.E., 2017, Prehistoric floods on the Tennessee River—Assessing the use of stratigraphic records of past floods for improved flood-frequency analysis: U.S. Geological Survey Scientific Investigations Report 2017–5052, 15 p., https://doi.org/10.3133/sir20175052.
- O'Connor, J.E., Atwater, B.F., Cohn, T.A., Cronin, T.M., Keith, M.K., Smith, C.G., and Mason, R.R., 2014, Assessing inundation hazards to nuclear powerplant sites using geologically extended histories of riverine floods, tsunamis, and storm surges: U.S. Geological Survey Scientific Investigations Report 2014–5207, 66 p. http://dx.doi.org/10.3133/sir20145207.

3.3.5.1.3 Questions and Answers

Question:

Is there any beer can chronology?

Response:

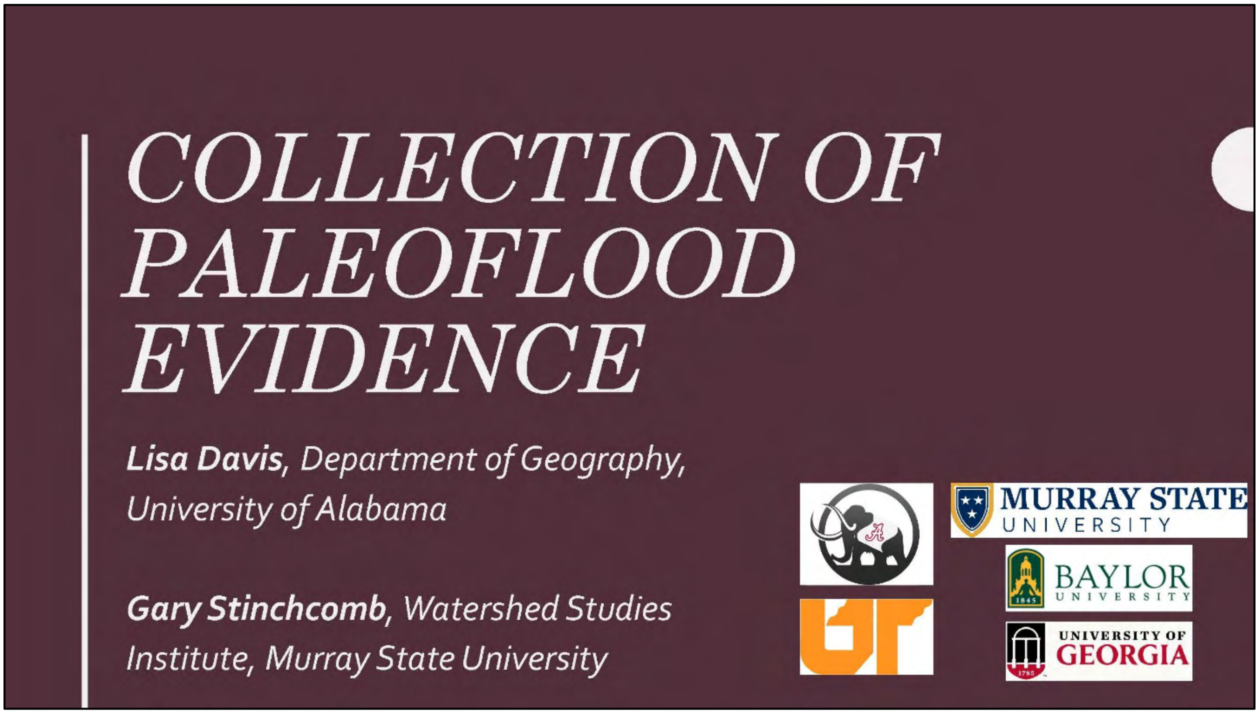
That's a good point. Beer can chronology -which is a real thing. So, people have used all sorts of things to date these things. And in the Black Hills, I've actually used socks which worked out great. People use beer cans… you can tell by when the can was made, and people use barbed wire to date these floods. We found plenty of beer cans, but they were all modern.

3.3.5.2 Collection of Paleoflood Evidence Lisa Davis*, Ph.D., University of Alabama; and Gary Stinchcomb, Ph.D., Murray State University (Session 1E-2; ADAMS Accession No. ML17355A094)

3.3.5.2.1 Abstract

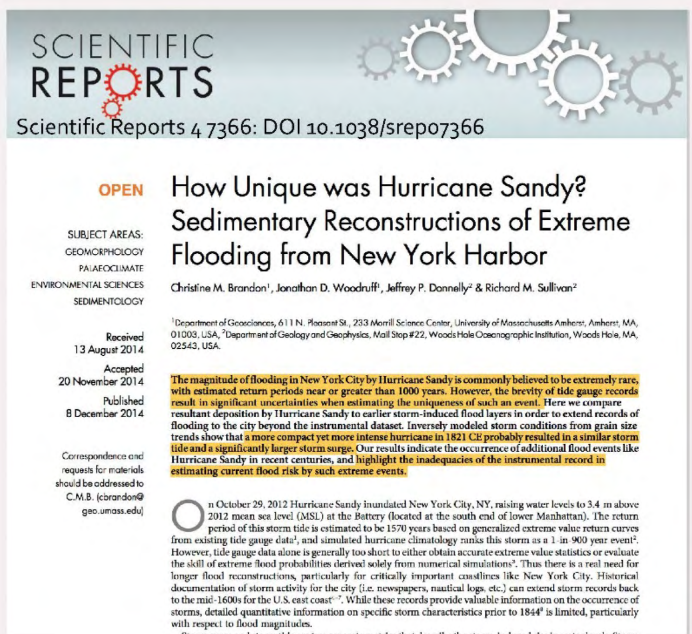
Despite significant advances in meteorological and hydrological forecasting in the last 50 years, catastrophic floods constitute one of the most globally persistent natural hazards. Instrumented discharge records rarely span more than 200 years, making them less likely to contain records of large floods, which tend to occur less frequently. Additionally, using instrumented flow records to understand flood variability in relation to climate, is more challenging since these records only span the time of human occupation. Paleoflood hydrology focuses on collecting and analyzing physical evidence of past floods that occurred before the instrumented record for flood risk assessment and to understand environmental change. Our presentation will demonstrate some of the basic principles of paleohydrologic research and present preliminary findings of a paleoflood record for the Tennessee River, as part of a broader effort to develop paleoflood data for flood frequency analyses for the Tennessee River.

3.3.5.2.2 Presentation



Hurricane Harvey: an unprecedented precipitation event?

Paleocontext can improve understanding of extreme events



SCIENTIFIC REPORTS
Scientific Reports 4 7366: DOI 10.1038/srep07366

OPEN

How Unique was Hurricane Sandy? Sedimentary Reconstructions of Extreme Flooding from New York Harbor

SUBJECT AREAS:
GEOMORPHOLOGY
PALAEOCLIMATE
ENVIRONMENTAL SCIENCES
SEDIMENTOLOGY

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13 August 2014
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20 November 2014
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8 December 2014

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[1]Department of Geosciences, 611 N. Pleasant St., 233 Morrill Science Center, University of Massachusetts Amherst, Amherst, MA, 01003, USA, [2]Department of Geology and Geophysics, Mail Stop #22, Woods Hole Oceanographic Institution, Woods Hole, MA, 02543, USA.

Correspondence and requests for materials should be addressed to C.M.B. (cbrandon@geo.umass.edu)

The magnitude of flooding in New York City by Hurricane Sandy is commonly believed to be extremely rare, with estimated return periods near or greater than 1000 years. However, the brevity of tide gauge records result in significant uncertainties when estimating the uniqueness of such an event. Here we compare resultant deposition by Hurricane Sandy to earlier storm-induced flood layers in order to extend records of flooding to the city beyond the instrumental dataset. Inversely modeled storm conditions from grain size trends show that a more compact yet more intense hurricane in 1821 CE probably resulted in a similar storm tide and a significantly larger storm surge. Our results indicate the occurrence of additional flood events like Hurricane Sandy in recent centuries, and highlight the inadequacies of the instrumental record in estimating current flood risk by such extreme events.

On October 29, 2012 Hurricane Sandy inundated New York City, NY, raising water levels to 3.4 m above 2012 mean sea level (MSL) at the Battery (located at the south end of lower Manhattan). The return period of this storm tide is estimated to be 1570 years based on generalized extreme value return curves from existing tide gauge data[1], and simulated hurricane climatology ranks this storm as a 1-in-900 year event[2]. However, tide gauge data alone is generally too short to either obtain accurate extreme value statistics or evaluate the skill of extreme flood probabilities derived solely from numerical simulations[3]. Thus there is a real need for longer flood reconstructions, particularly for critically important coastlines like New York City. Historical documentation of storm activity for the city (i.e. newspapers, nautical logs, etc.) can extend storm records back to the mid-1600s for the U.S. east coast[4–7]. While these records provide valuable information on the occurrence of storms, detailed quantitative information on specific storm characteristics prior to 1844[8] is limited, particularly with respect to flood magnitudes.

Research Questions

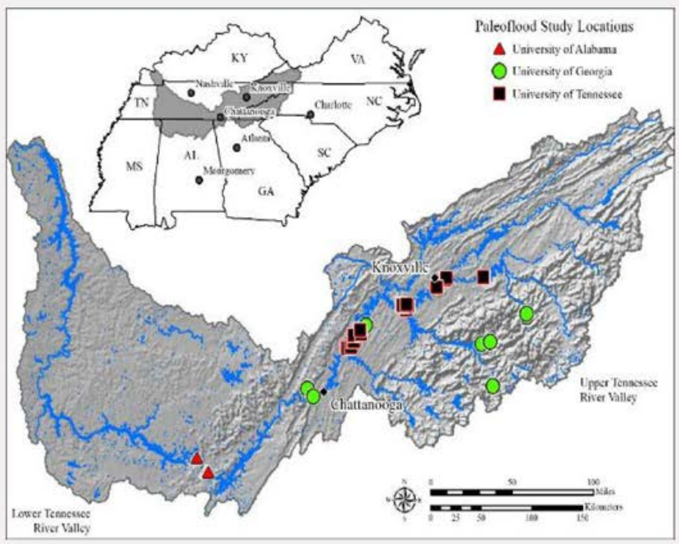
Do paleoflood indicators of extreme floods exist in the Tennessee River basin?

Can these paleoflood indicators be used to estimate peak stage, **discharge**, and **flood age**?

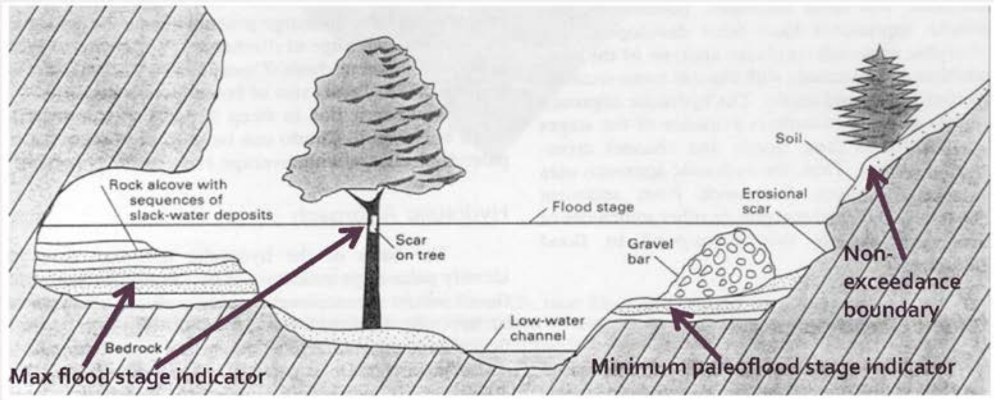
Are the proxies reproducible among different teams?

Flood of record (1867) on the Tennessee River at Knoxville, TN (image from McClung Museum, University of Tennessee)

The Tennessee River



Methods



Schematic from: Jarrett, R.D., 1998. Paleoflood investigations to assess extreme flooding for Elkhead Reservoir, Northern Colorado: Proceedings from the First Interagency Hydrologic Modeling Conference, Las Vegas, NV.

Methods: multi-pronged, multi-site approach

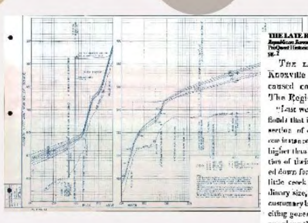
Instrumented Record

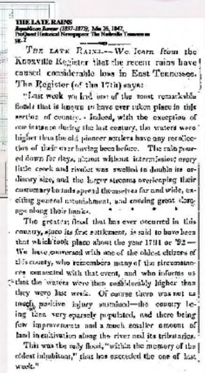
Historic Record

Tree Ring Record

Sedimentary Record

Present → *Past*





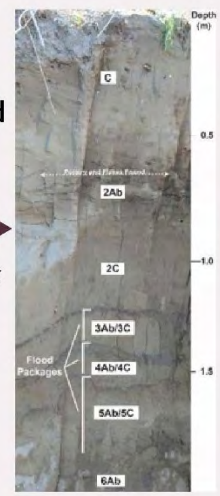
THE LATE RAINS

THE LATE RAINS.—We learn from the Knoxville Register that the recent rains have caused considerable loss in East Tennessee. The Register (of the 17th) says:

"Last week we had one of the most remarkable floods that is known to have ever taken place in this section of country. Indeed, with the exception of one instance during the last century, the waters were higher than the old pioneer settlers have any recollection of their ever having been before. The rain poured down for days, almost without intermission; every little creek and rivulet was swelled to double its ordinary size, and the larger streams overleaping their customary bounds spread themselves far and wide, exciting general astonishment, and causing great damage along their banks. * * * *

The greatest flood that has ever occurred in this country, since its first settlement, is said to have been that which took place about the year 1791 or '92.—We have conversed with one of the oldest citizens of this county, who remembers many of the circumstances connected with that event, and who informs us that the waters were then considerably higher than they were last week. Of course there was not as much positive injury sustained—the country being then very sparsely populated, and there being few improvements and a much smaller amount of land in cultivation along the river and its tributaries.

This was the only flood, "within the memory of the oldest inhabitant," that has exceeded the one of last week."



River Terrace Sites

- All teams sampled terrace deposits with the goal of reconstructing the number and relative size of floods experienced at each location
- Landforms sampled on terrace surfaces included paleomeander bends, relict natural levees, and topographic lows

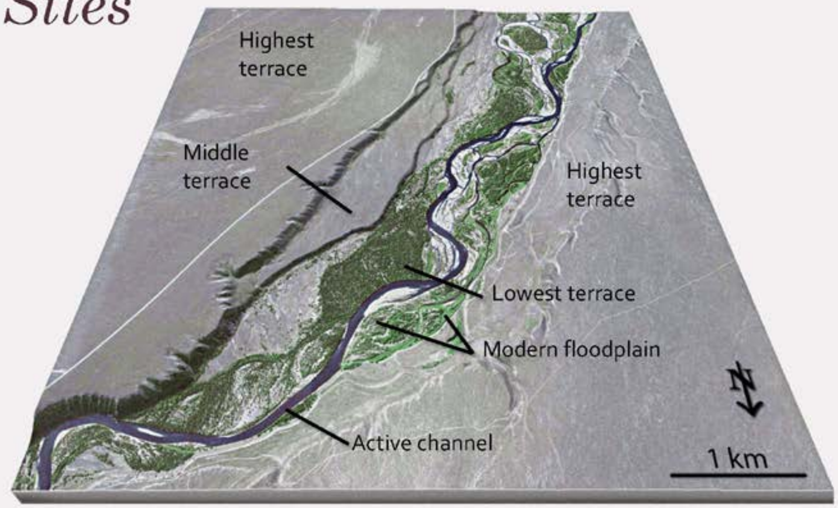
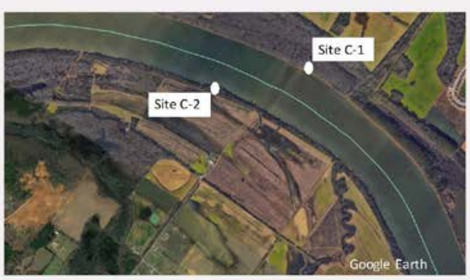
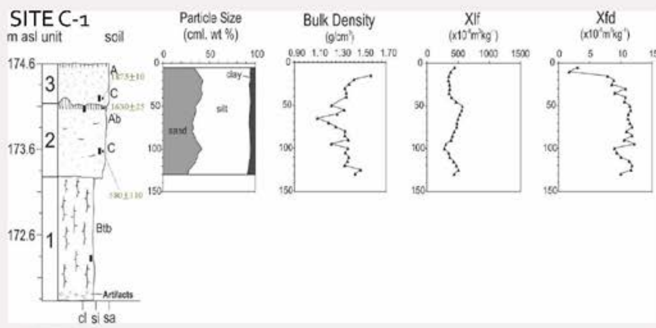


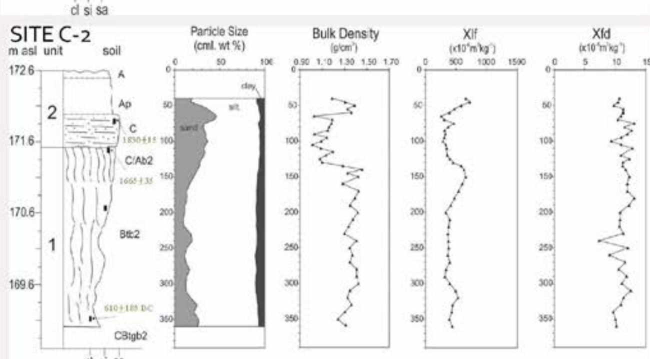
Figure from: Reynolds, S., Rohl, R., Johnson, J., Waylen, P., Francek, M., 2014. Exploring Physical Geography. McGraw-Hill Education.

Terrace Sites C-1 and C-2

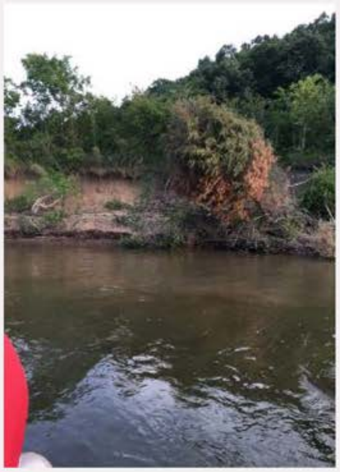
4 flood deposits



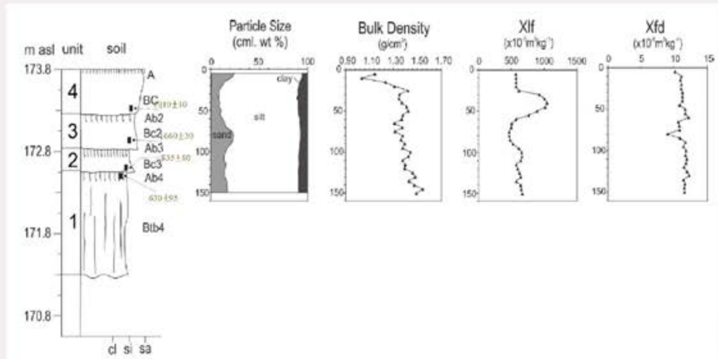




Terrace Sites

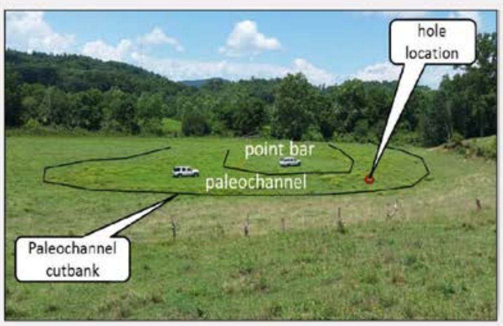


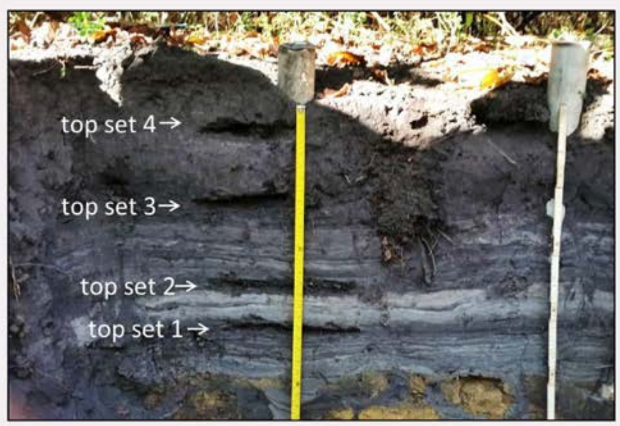
4 flood deposits



Terrace Site A-6

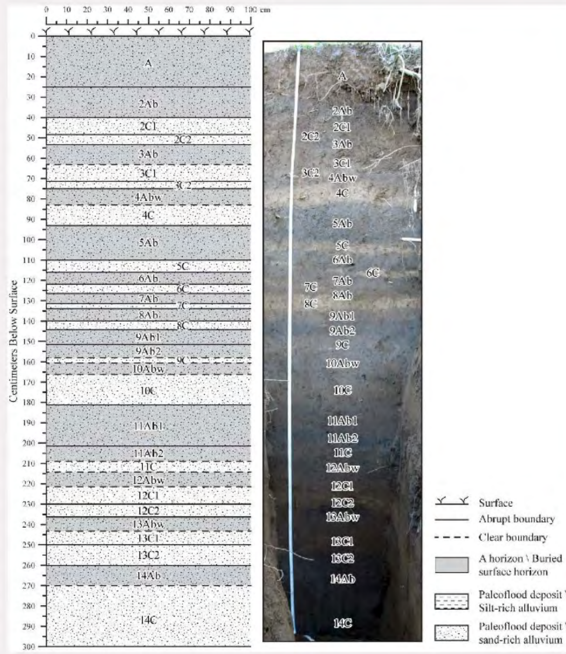
- 5 flood deposits dated to: ~1607, ~1867, ~1875, ~1886, ~1917





Terrace Site B-21

- 12 flood deposits
- Flood of record (1867) found at multiple sites
- Two sites had flood deposit that radiocarbon-dated to early 1600s



Bluff, Cave and Canyon Sites

- Slackwater deposits
- Potential for *max paleostage reconstruction*

MURRAY STATE UNIVERSITY

BAYLOR UNIVERSITY

Fig. 10. Stream cobbles wedged into a group of speleothems.

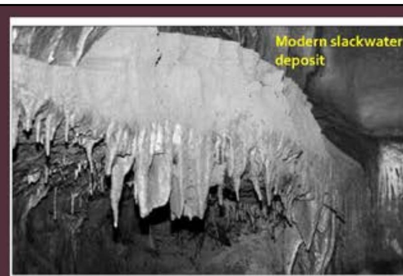


Fig. 9 Sand deposited on a flowstone shelf.

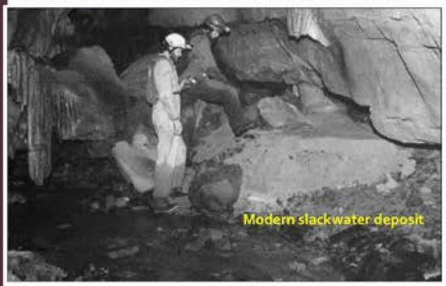
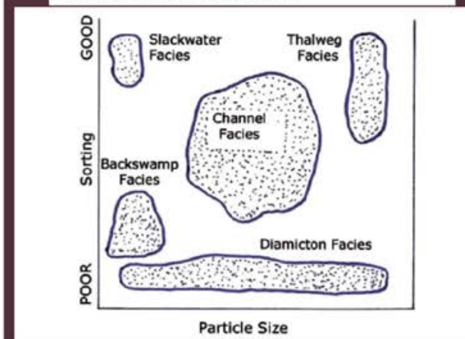


Fig. 8. The post-storm stream channel. The only evidence of massive sediment movement is the sand bar on the bank of the stream.

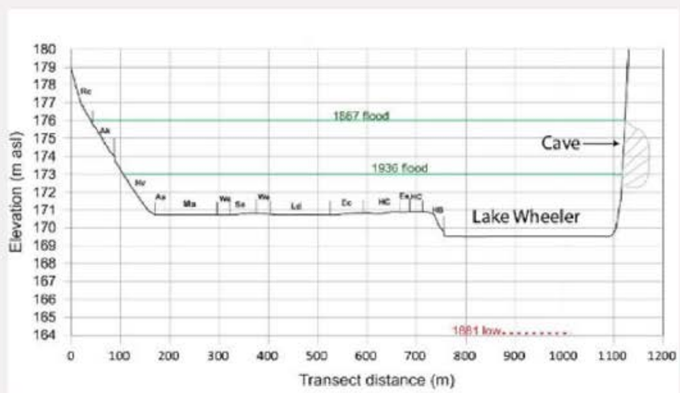


Cave sediment facies figure from: Studies of Cave Sediments: Physical and Chemical Records of Paleoclimate, Edited by Sasowskey and Mylorie.
Figs. 8-10 from: Gundy and White, 2009. Sediment flushing in Mystic Cave, WV, USA, in response to 1985 Potomac Valley flood, International Journal of Speleology 38(2): 103-109.

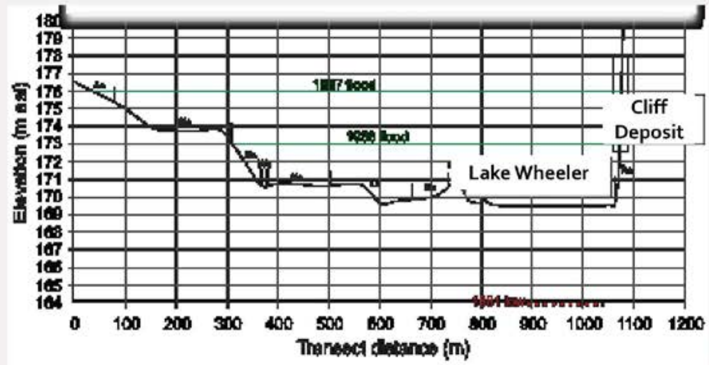
Cave deposits

MURRAY STATE UNIVERSITY

BAYLOR UNIVERSITY



Bluff deposit

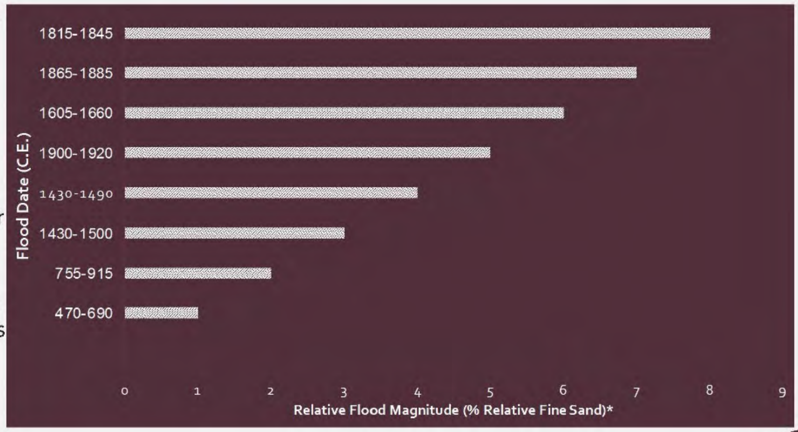


Boulder sheltered deposits

Flood deposit located on downhill/stream side of large in canyon of tributary to TN River

Summary of findings to date

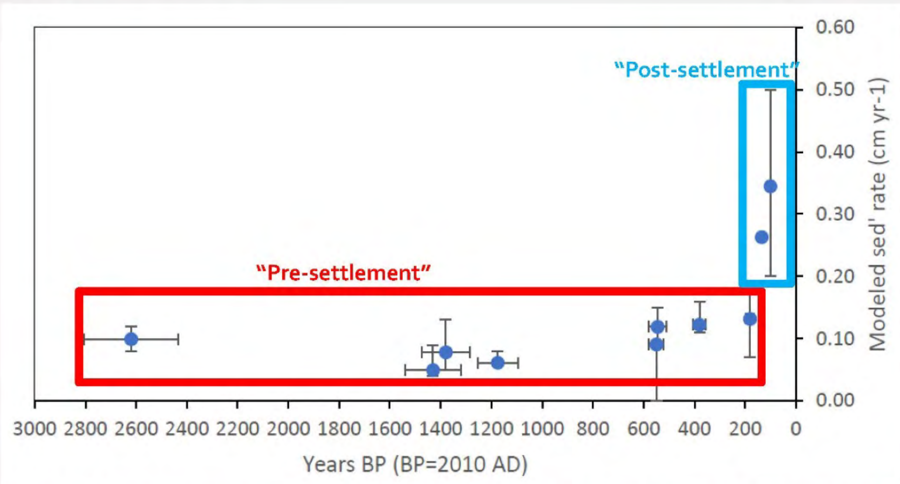
- Extended the flood record of the TN River by ~ 1200 years
- Discovered evidence of several pre-historic, large floods
- Flood of 1847, validated by deposit dated to 1830 +/- 15? This flood potentially larger than the flood of record?
- Some of the (pre) historic floods correlate between all three research groups, such as the 1910, 1867, 1630 floods
- All of the surfaces predicted to be inundated by TVA's extrapolated water surface elevations for the 1867 flood were found to have been inundated



*Method based on Leigh, D.S., 2017. Vertical accretion sand proxies of gaged floods along the Upper Little Tennessee River, Blue Ridge Mountains, USA. Sedimentary Geology, *Article in Press*, https://doi.org/10.1016/j.sedgeo.2017.09.007.

Summary of findings to date

Modeled sediment accumulation rates are faster during past 170 years, compared to older record.



These rates are consistent with pre-settlement and post-settlement sedimentation rates observed along Upper Little Tenn. R. basin (Wang and Leigh, 2015)

3.3.5.2.3 Questions and Answers

Question:

You brought up a very good point. In the northern part of Pennsylvania, there was a lumbering boom that occurred, and the mountains were literally devoid of any lumber and then sufficient flooding occurred. People would argue that because of the context of that flooding, could that repeat itself? Meaning that unless you cut down all the trees again in northern Pennsylvania, would you expect to see those kinds of floods. So, could you give us some perspective on the Tennessee River Valley with regard to the context of the various floods you've seen? Do you have any reason to understand why they occurred?

Response:

That’s something very interesting. Until we really nail down the timing of events, we can't get a good handle on the mechanisms. Right? So, the other thing to remember is that the more sites we have, the more robust picture that we get. So, for example, the 1600 flood that all of the teams picked up, that's very interesting to us because that may speak to its magnitude. The fact that it happened everywhere in the basin is very interesting and that is a time that coincides at a time in the eastern United States where there's not a lot of written record about flood information. But we do know that and say for example in New England, the pilgrims were complaining a lot about springtime flood at that particular time. So now maybe with this information from the Tennessee River, maybe we're getting a broader picture of what the climate was like in the eastern US and not just where they were. Maybe that was a pattern that was bigger regionally. So, once we get more of the timing information and that the timing of those floods validated at more sites, we can speak more about mechanisms… weather or climatological or tied to human initiated mechanisms.

Question:

With respect to the pre-settlement and post-settlement sedimentation, obviously you'll see different rates. Do you see differences in the sediment types as well?

Response:

Yes. Initially, when we started looking at these profiles, the one thing that stood out repeatedly was that there was a well-developed soil at depth and then you would see these very weakly developed soils and flood deposits near the surface. More often than not, those date to the last two to four hundred years, but at one of the sites we did find one I think was the bond site…there's one that dated like five, six hundred years ago. My initial assumption I guess is flawed…I thought that the soil stratigraphy alone was saying something about this change from pre-settlement to post-settlement, but there's this 600-year-old flood that kind of just comes out of nowhere. It's clearly pre-European settlement so I don't know how to make sense of that yet. Now the other thing that we've been looking at is we've been looking at the types of organic molecules present in the flood material and one thing we're finding is there's abundance of charcoal or charred material in the more recent stuff. That may or may not be related to pre-versus post settlement. I don't know if charcoal was really huge in the Tennessee River basin and I know it was huge in the Northeast but if they were charcoaling, I guarantee you there was char flying about everywhere. So anyway, I don't know how you would source the char in the flood deposit back to it, but the char is a tantalizing clue we need to explore that more.

Question:

I had a similar question to the first one. Can you tell when the floods occurred? Is it in the spring or fall? Because it's a different concern whether it was snowmelt versus flash flood depending on how to mitigate against those scenarios and whether it's a big concern or not for certain facilities.

Response:

We didn't include information in this, but we do have a dendrochronologist who's working with us named Matt Farrell at the University of Alabama one of the things that he specializes in is looking at cellular damage in the tree rings. That cellular damage only has potential to happen when the trees are saturated for a length of time during the growing season so essentially when you find this you know that the flood happened in the spring or the summer. So, there is potential to find seasonal information about floods in the record, but unless we get like an oxbow lake somewhere that had seasonal deposition but as far as I'm aware, no one has found that. You do find that in glaciated environments where the melt water flow is very seasonal, you get what are called barb deposits where there's seasonal deposition, but our deposits are of an age where even if there was a seasonal signature when they were first laid down it's probably been destroyed by the weathering process.

Question:

Do you guys have any plans to maybe assimilate some of those data and maybe have some spatial characterization to gain some insight on prehistoric hydrology?

Response:

That's a good idea. That might just happen through the research publication process, us all combining data and telling sharing that through the research literature. Or it may happen as part of some other workshop or something tied to this collaborative effort. We're very much open to that and one of the things is that we feel like we're breaking new territory here in science and not just like flood science either. This is a unique opportunity for us to combine paleo study information in a way that the academic studies don't typically have. You typically do your own site, one site, and you do it very detailed and we're combining these detailed studies across the whole basin to get a basin-wide picture which is really robust in a way that hasn't typically been done. So, I think there's a lot of value to that idea and I know there's a lot of interest among the broader group in pursuing that.

Question/comment:

I wanted to add that this sort of thing is very unique in the way these studies are done… you do your own thing, you answer this question, and then you move on. For the first time now and this is a very big basin, yet we are covering different spatial scales of this big basin. I'm sure TVA is thrilled and they're going to get all this information for essentially free, but why not combine it and really nail down what's happening in the basin.

Response:

In particular that question about human occupation as a valley and its effects on flood surface hydrology… I mean that is something that interests a lot of us. In particular David Lee has been looking at whether or not there the soil marker…when that transition happened… if there's a chemical marker that coincides with that. So that others who don't have a lot of money to identify that in their site …then we can increase number of sites a lot more easily… there's momentum for that.

3.3.6 Day 2: Daily Wrap-up Session / Public Comments

Question: (Audience member)

I have a question for the paleo people. In general, do you take into account upstream infrastructure for older data and how an event would occur today vs. the past?

Response: (John Weglian, EPRI)

We have an ex TVA person at the table, I don't know if any current TVA people are in the room right now, but they do have hydraulic for both with and without the dams. So, the floods that we're looking for with this Paleo Flood information predate the existence of dams, but that tells us something about how much water came down the river and so you can use what they call a Naturals model to evaluate what that water level would have done along the river. That's how we can correlate these different floods in different locations and things like that, but then you can put that same information into their new hydraulic models that include the actions of the dams and then they can include in that if the dam models" saw of this much level… how would it operate and what is going to affect the downstream flow rates. So, there are ways to correlate what an amount of flow discharge… how that would operate today with the man-made structures in place.

Comment: (Audience Member)

You're saying we use all that old data we need to remodel with the new infrastructure before we use that datum

Response: (John Weglian)

Correct. So, if you're trying to assess risk at a particular site and you have information on how that river operated or an event that happened on that river say 400 years ago or a thousand years ago, you need to assess how that same event would look in today's watershed to assess the site that you're particularly interested in. Depending where you are in the country that may be relatively easy, it may be extremely complicated, depending on what man-made structures are now on the watershed. That's all a part of the puzzle that you have to put into your analysis to assess your current risk at a particular site.

Response: (USBR)

I was going to follow up on that. At Reclamation there's definitely multiple approaches to looking at both unregulated and regulated frequencies. And I know at Reclamation that we definitely look at both depending on the question that's being asked and there's multiple methods to address that simplified mass balance. And methods or statistical methods doing correlations to pre and post dams and there's a multiple method to do it. At the end of the day, we're mostly interested in the regulated flow frequencies, but it just depends on the question being asked.

Question:

We have a question on the webinar for Dr. Ryberg. This question comes from Keith Kelson . Dr. Ryberg how have the studies along the Red River and the Souris River handled variable stages and discharges related to ice affected floods?

Response: (Karen Ryberg)

That is a good question. The data from the Red River at Winnipeg is from Manitoba water stewardship, and its naturalized flow to take into account changes in regulation there. They have estimated flows under ice as part of that and I don't know all the details on that. On the Souris River, generally, ice jamming has not been an issue. There are ice affected flows that the USGS has marked “provisional” until they are analyzed, and then in some cases adjusted but they are considered good estimates of flow. We haven't done anything to adjust for ice on the Souris River.

Question: (Audience Member):

I have a question for Ruby, but I guess she's gone. I was curious about what the postulated mechanism that would impact the decrease in storm speed that she was talking about. Some of the forecasting of some of the storm characteristics like what caused the decrease in these storms’ speeds?

Response: (Rajiv Prasad, **PNNL):**

Good question and I don't know the exact answer to that but some of it might lie in how the large-scale climate patterns are changing and there are some studies that are relating these climate patterns both in the Atlantic and in the Pacific to how these tracks might be changing. But there’s a forward shift and that is moving some of the stuff to the north.

Question: (Audience Member):

Another question I had for her but maybe you can answer it. She was looking at some of the MLC storm types and that's great looking at these different storm types. Are you guys planning on doing any projections for tropical cyclones or any other controlling storm types in that region?

Response: (Rajiv Prasad, PNNL):

We are not planning on doing any projections. All we are doing in this study is compiling what is already known and published. We don't plan to do anything new in this project.

Response: (Joe Kanney, NRC):

For that project that we have with PNNL, what we've asked them to do is basically help us sift through a lot of the results that are coming out of the climate science community. It’s something we need a lot of help to take that on board in terms of studies are significant, what trends they are showing, and then what impact it might have on hydrology. But also, other factors that influence nuclear power plants. So yes, they're basically helping us sift through the results that are coming out of the climate science community.

Comment: (John Weglian, EPRI):

I like to talk about something Steve from INL asked… whether we could tell if it was winter versus summer, whether there was an ice component or snow component on it. With the Paleo flood data, I'd like to say that it probably doesn't matter. Something I was trying to say earlier in one of my talks and I think I did a very poor job of doing it is some of the major extreme events are probably not just a hurricane or just a meso-scale convection. It might be a hurricane hits a nor'easter and the combination of those is much different than an individual storm type. I think that goes back to something you were asking about there. But the point is that if those things have ever happened, they may have left evidence and that's what we're looking for in the paleo flood evidence. We don't necessarily know what caused it but we know that at least once in X number of years we have had a major event up to a certain level and some people may try to explain what kind of event that could have been or something, but from a risk assessment at a particular site, in this case, the nuclear power plant, it doesn't necessarily matter so much what exactly it was but it does matter that it did occur and how big it was. We've got our synthetic modeling and our stochastic models and all these kinds of things but if you can say in the last thousand years, even with all that, I had a flood up to here, that's a real data point that we can use to assess the risk. If you can alternatively say, I find no evidence that we ever exceeded this amount, that's also a good data point that we can use to help assess their risk. It doesn't necessarily matter that we can't reconstruct what happened, it's more important that we can tell how bad it has gotten in the past and that's what it can show us I think.

Comment: (Joe Kanney, NRC)

Some of those questions may matter, not in terms of whether you saw it or not but how you interpret on that data and how you use it statistically. Essentially, the main question would be: do I have one population of flood causing mechanisms or should I model this as coming from multiple populations? So, to that extent that information can be useful in how you interpret that data.

Comment: (Tessa Harden, USGS)

Just to add something. I think if you look at the gauge record and for the Tennessee River, the large storms which are quite a bit larger than say everyday storms or so. They all happen in the spring so if you get maybe in the Paleo food record you see all around that certain discharge.

Comment: (Steve Prescott)

Snowmelt versus a flash flood coming through gives different response times. If there's way to know that then you can gauge how many of these events are of those types and bin them and know how to respond and what frequency those type of events are.

Comment: (Karen Ryberg)

I just wanted to follow up a little bit more on the ice question. I'm not sure if I totally understood what they were getting at. When we measure peak streamflow and there are ice effects, someone goes out and makes a measurement because we know there's a change in the stage discharge relationship. You wouldn't use the rating curve that you would under open water, so we make those adjustments and those adjustments have been made for a long time. But even if you've got this hundred year record you're excited about, back in time less than that [100 years] you don't know what may have happened. In particular historical floods that have a code 7 in the USGS database before the systematic record those have been entered as point estimates in the database which in retrospect was not a good thing because there's a huge degree of uncertainty, but that database was developed in the 1960s when you had to worry about every digit taking up more memory in the database. So, it's a point estimate, and if I had a huge pot of money and people to do it… it would be fantastic if the USGS would go back to all of those code seven peaks, historical peaks, and put in an interval estimate. That would give you a better sense of that uncertainty which in some cases would be caused by ice uncertainty in other places. So, as we go back further in time there's definitely more uncertainty in the data related to ice and to other things.

Comment: (Audience Member)

I have just another comment on the ice. I worked on the Delaware River a couple years ago and I was looking at these profiles much like we're doing on the Middle Tennessee River and its fine-grain alluvium, but occasionally what we would find are large cobbles showing no signs of reworking by Native Americans, and underneath the large cobbles were fine pebbles. We kept finding these layers of them in particular units and one of the things we were thinking was that these cobbles were ice wrap debris. You'd be basically plucking grains off the side of the channel, so you have bed load where you have large cobbles and underneath those large cobbles are the fine pebbles like an armoring effect I guess. There's evidence of ice wrap debris but the problem is you spend all day digging a pit and you find evidence of it but if I dig four or five meters down and dug a pit I might not see that and so it's like a shot in the dark. I think it does exist. There's potential there to identify say like a flood from ice raft debris but it is a shot in the dark.

Question: (Audience Member)

This is a question for Jennifer, Tess, and/or Joe related to the paleo flood study in the Tennessee River Gorge. I was just kind of thinking during the presentation, you're talking about the gorge being kind of like a dam in some respects and then it opens up there above Williams River and then Chattanooga so there's a lot of volume so in some ways Chattanooga and that whole valley upstream is kind of a reservoir. I'm wondering if you guys are going to, when you're doing the hydraulic modeling, include that area upstream and get an idea of some of the volumes. Or maybe the end flow may be different than the flows that you're seeing through the gorge and what that hydraulic model going to look like.

Response:

We have some sites that are right at the mouth or a little upstream so that'll be included in the model. We haven't really talked about model parameters, but it should be included…hopefully it will be included.

3.3.7 Day 2: Poster Session

Session Chair: Thomas Aird, NRC/RES/DRA/FXHAB

3.3.7.1 Poster Abstracts

3.3.7.1.1 Probability-Based Flow Modeling Using the Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS) Brian Skahill, U.S. Army Corps of Engineers, Engineer Research and Development Center, Coastal and Hydraulics Laboratory

3.3.7.1.2 Reclamation's Paleoflood Database: Design, Structure and Application. Jeanne E. Godaire, Kurt Wille, and Ralph E. Klinger, U.S. Bureau of Reclamation, Technical Services Center

The Bureau of Reclamation paleoflood database was developed beginning in 1999 as an outgrowth of the global paleoflood database that was being developed at the University of Arizona through Dr. Katie Hirschboeck in order to provide a digital archive for paleoflood data in the United States. Currently, the database is internal to Reclamation and exists mainly as a data repository, containing some published paleoflood data and Reclamation paleoflood studies that were primarily developed at or near Reclamation facilities. This database is an important resource for paleoflood investigations and hydrologic hazard assessment but has been underutilized due to a lack of tools to effectively synthesize the data for projects and research. However, the database could be used more significantly to efficiently investigate research questions related to hydrologic hazards, climate change or other related topics. Tools associated with the database have been developed to extract data, attach related data, and create complex queries to assist in paleoflood research. Reclamation has been improving the database structure and graphical interface using a combination of Microsoft Access and ArcGIS. Data are stored as relational tables with searchable fields that can be queried using spatial or field-based queries.

3.3.7.1.3 Late Holocene Paleofloods along the Middle Tennessee River Valley. C. Lance Stewart and Gary E. Stinchcomb, *Department of Geosciences and Watershed Studies Institute, Murray State University*; Steven L. Forman, *Department of Geology, Baylor University*; Lisa Davis and Rachel Lombardi, *Department of Geography, University of Alabama*; Emily Blackaby, Owen Craven and William Hockaday, *Department of Geology, Baylor University.*

Sediment stored in floodplains and low alluvial terraces along the middle Tennessee River reflects flood frequency and magnitude during the past ca. 1500 years. This study uses the stratigraphy, sedimentology, ^{13}C NMR analysis (nuclear magnetic resonance) and geochronology of three alluvial terraces to infer past flooding. Buried soils at the three locations are older than ca. 630 CE and suggest a multi-century period of landscape stability. Multiple flood deposits are separated by weakly developed soils, indicating an increased flood frequency until ca. 1910 CE. Optically-stimulated luminescence dates of flood deposits yield ages of 580+/-110, 835+/-80, 1460 +/-30, 1465+/-35, 1660+/- 30, 1830+/-15, 1875+/-10 and 1910+/-10 CE. Age-depth modeling shows increased sediment accumulation rates following ca. 1800 CE. The geochronology, when combined with ^{13}C NMR, shows an increasing flood sedimentation rate during the past 200 years associated with a decrease in the abundance of charcoal and increase in the abundance of lipids. These data suggest that the more recent flooding is more frequent and contains more C with higher oxidation potential. Particle-size analysis of historic floods demonstrates an increase in sand content with increasing flood magnitude, which is consistent with previous work upstream. The highest percentage of sand is found within flood deposits dated to 1830+/-15, 1460+/-30 and 1875 +/-10 CE, the latter of which coincides with the 1867 CE historic flood of record along the Tennessee River. The high magnitude flood of 1830+/- 15 CE is consistent with a USGS paleoflood analysis upstream that documents a paleoflood occurring ca. 1600-1800 CE that was higher in elevation than the historic flood of record. The earliest observed flood deposits appear to occur during transition into the Medieval Climate Anomaly between 800 and 1300 CE with increased flood magnitude through the Little Ice Age (1400-1800 CE), and with peak magnitude occurring 1830+/-15 CE.

3.3.7.1.4 A regional chronology of floods and river activity during the last 10,000 years in the Eastern U.S. Lisa Davis, Rachel Lombardi*; Department of Geography, University of Alabama,* Gary Stinchcomb*; Watershed Studies Institute, Murray State University,* C. Lance Stewart*; Department of Geosciences, Murray State University,* Matthew D. Therrell*; Department of Geography, University of Alabama,* Matthew Gage*; Office of Archeological Research, University of Alabama .*

Most paleoflood analyses are conducted at a single site or a small number of sites within a single river basin. These studies provide detailed chronologies of river activity, such as flooding, spanning hundreds or thousands of years, which can be used to decrease uncertainty in flood frequency analyses. Site specific reconstructions, however, have limited applicability to understanding river activity at larger spatial scales, such as an entire basin or multiple basins within a region or for understanding drivers of regional and continental-scale changes in the timing or spatial occurrence of floods. This poster presents a regional chronology of river activity over the last 10,000 years for the Eastern U.S.—the first of its kind for this region. The chronology was developed by compiling and combining hundreds of site-specific paleoenvironmental reconstructions containing radiocarbon-dated flood and rainfall-related depositional events from the research literature and unpublished archeological reports. This Eastern U.S. regional river activity chronology is applicable to flood frequency analyses in three specific ways: (1) it can be used to understand the spatial occurrence of floods in the Eastern U.S. over millennia; (2) it can be used to examine how flood frequency has changed throughout the region and within major river basins of the Eastern U.S. over millennia; and (3) it could be used to validate site-specific reconstructions of floods and paleoenvironmental change to determine whether their findings are applicable to broader geographic areas, such as an entire river basin.

3.3.7.1.5 Critical Review of State of Practice in Dam Risk Assessment David Watson, Scott DeNeale, Brennan Smith and Shih-Chieh Kao, Oak Ridge National Laboratory(ORNL); Gregory Baecher, University of Maryland.

Dams in the United States are aging and in dire need of refurbishment. The American Society of Civil Engineers 2017 Infrastructure Report Card states that the average age of the 90,580 U.S. dams is 56 years with 17% classified as high-hazard potential dams with potential for loss of life and another 13% labelled as significant hazard potential dams with potential for significant economic losses. An estimated $45 billion is needed to repair the high-hazard potential dams alone. Potential detrimental impacts of dam failure include flooding of downstream nuclear power plants.

This project will focus on summarizing and providing a critical review of the state of practice in dam failure risk analysis , with a particular emphasis on developing and quantifying fragility information. The objective of this project is to assist NRC in developing the technical basis for guidance on application of state-of-the-practice approaches, methods and tools for dam risk analysis to inform assessment of flood hazards due to dam failure.

This project will seek to summarize and provide a critical review of approaches and methods for developing fragility curves for key components, systems, and procedures that contribute to the overall fragility of the dam. This will include, but not be limited to:

- •Probabilistic geotechnical analysis methods for assessing embankment/foundation/abutment stability
- •Reliability of key components such as gates, gate hoists, valves, etc.
- •Systems analysis approaches
- •Reliability of operational and emergency procedures
- •Methods for estimating breach initiation and progression

The project will focus on assessing methods for characterizing and quantifying key uncertainties, as well as propagating these uncertainties through the risk analysis procedure to support risk-informed decision-making. To accomplish the objectives of this project the project team will: (1) Assist the NRC in organizing and conducting a workshop to review the current state of practice in dam risk analysis. The workshop participants will include leading experts from other federal agencies, academic researchers and private industry. International perspectives will also be sought; (2) Provide a summary of the current state of practice in dam risk analysis with a particular focus on development of fragility information for key components, control systems, and operational procedures; (3) Provide a critical review of how key process uncertainties, their characterization, and the degree to which they are propagated in state of practice approaches; (4) Prepare NUREG/CR reports summarizing activities 1-3 and providing guidance on use of state-of-practice dam risk assessment approaches, methods and tools for informing assessment of flooding hazards due to dam failure; (5) Conduct a knowledge transfer seminar at the NRC Headquarters in Rockville, MD covering the topics in items 1-4 with a focus on item 3. The guidance developed under this project will support and enhance NRC's capacity to perform thorough and efficient reviews of license applications and license amendment requests. They will also support risk-informed significance determination of inspection findings, unusual events and other oversight activities.

3.3.7.1.6 Application of Point Precipitation Frequency Estimates to Watersheds Shih-Chieh Kao and Scott DeNeale, Oak Ridge National Laboratory

All nuclear power plants must consider external flooding risks, such as local intense precipitation(LIP), riverine flooding, flooding due to upstream dam failure, and coastal flooding due to storm surge or tsunami. These events have the potential to challenge offsite power, threaten plant systems and components, challenge the integrity of plant structures, and limit plant access. Detailed risk assessments of external flood hazard are often needed to provide significant insights to risk informed decision makers. Many unique challenges exist in modeling the complete plant response to the flooding event. Structures, systems, and components (SSCs), flood protection 4features, and flood mitigation measures to external flood may be highly spatial and time dependent and subject to the hydrometeorological, hydrological, and hydraulic characteristics of the flood event (antecedent soil moisture, precipitation duration and rate, infiltration rate, surface water flow velocities, inundation levels and duration, hydrostatic and hydrodynamic forces, debris impact forces, etc.). Simulation based methods and dynamic analysis approaches are believed to be a great tool to model the performance of structures, systems, components, and operator actions during an external flooding event. In support of the NRC PFHA research plan, INL is tasked to develop such new approaches and demonstrate a proof of concept for the advanced representation of external flooding analysis. This project was started in September 2014 and finished in April 2017. It developed a work plan and framework to perform a simulation based dynamic flooding analysis (SBDFA). The SBDFA framework was then applied to a LIP event as a case study. A 3D plant model for a typical PWR and 3D flood simulation models for the LIP event were developed. A state-based dynamic PRA modeling tool, EMRALD, was used to incorporate time-related interactions from both 3D time-dependent physical simulations and stochastic failures into traditional PRA logic models. An example EMRALD model was developed to represent two accident sequences in a simplified traditional PRA model for general transient. 3D simulation elements were incorporated into the EMRALD model and could communicate with the PRA logic. The integrated EMRALD model was run with 3D flooding simulations and millions of Monte Carlo simulations. The EMRALD model results were compared with the corresponding traditional PRA model results. Insights and lessons learned from the project are documented for future research and applications.

The project shows that dynamic approaches could be used as an important tool to investigate total plant response to external flooding events with their appealing features. It can provide visual demonstration of component or system behavior during a highly spatial and time dependent flood event. It could provide additional important insights to risk informed decision makers. The dynamic approaches could also play a supplemental role by supporting the development or enhancement of a static PRA with the insights from the dynamic analysis or performing a standalone analysis that focuses on specific issues with limited sequences and components (e.g., FLEX).

3.3.7.1.7 Quantification of Uncertainty in Probabilistic Storm Surge Models Norberto Nadal-Caraballo, Victor Gonzalez and Efrain Ramos-Santiago, U.S. Army Corps of Engineers, Engineer Research and Development Center, Coastal and Hydraulics Laboratory

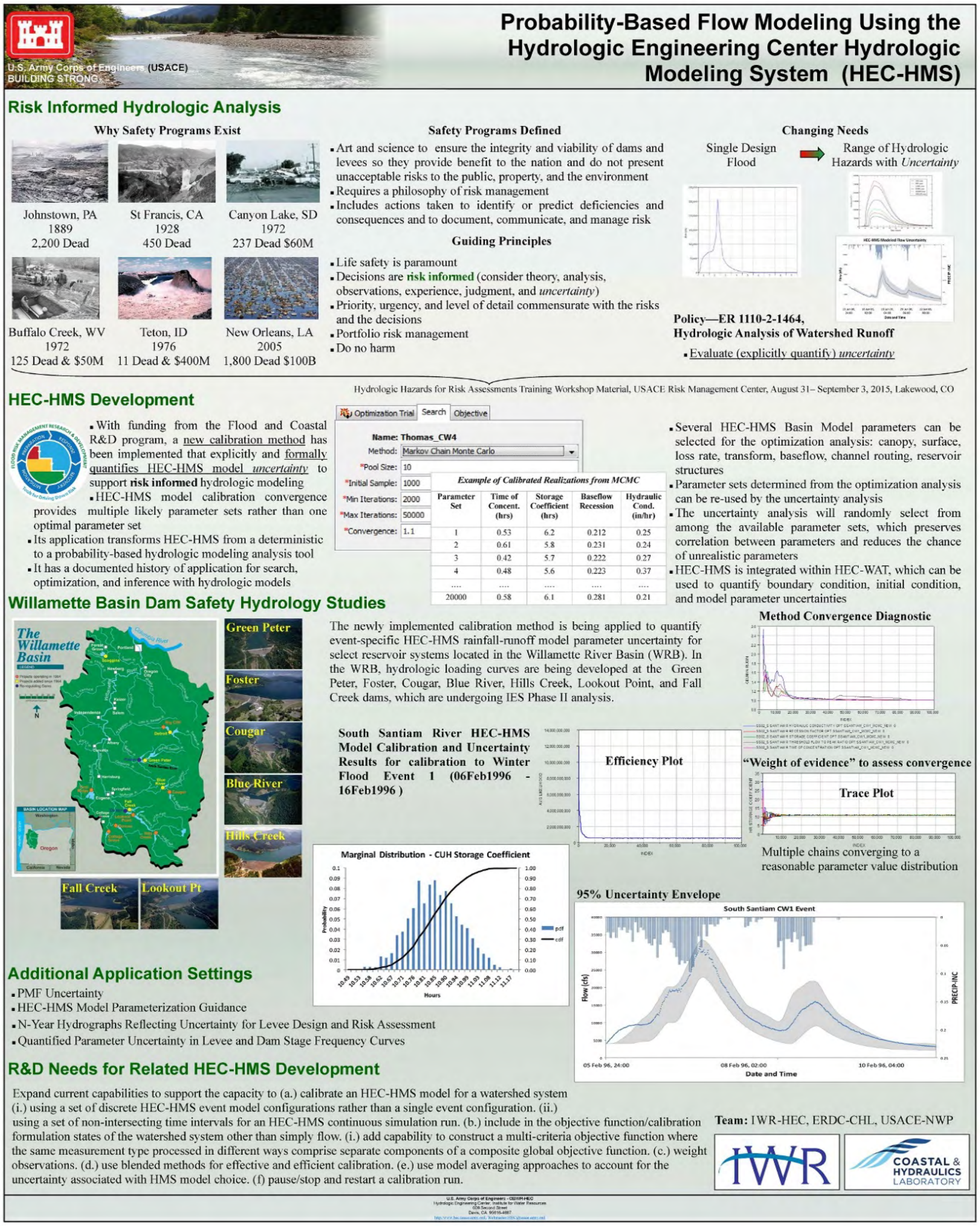
3.3.7.1.8 Modeling Plant Response to Flooding Events Zhegang Ma, Curtis L. Smith and Steven R. Prescott, Idaho National Laboratory, Risk Assessment and Management Services; Ramprasad Sampath, Centroid PIC, Research and Development

3.3.7.1.9 Stratigraphic Records of Paleofloods, Geochronology and Hydraulic Modeling to Improve Flood Frequency Analysis Tessa Harden, U.S. Geological Survey, Oregon Water Science Center.

A rich history of large late-Holocene Tennessee River floods is preserved in caves and alcoves throughout the Tennessee River Gorge area near Chattanooga, Tennessee. Preliminary stratigraphic analyses, coupled with geochronologic techniques, show evidence of at least four floods occurring in the last ~3,000 years with possible discharge estimates greater than or similar to the 1867 peak of record (460,000 ft3/s at Chattanooga, Tennessee). One of those floods may have occurred in the last 400 years and has an estimated discharge at least twice the magnitude of the 1867 flood. At least 1–2 additional large floods with estimated peaks similar to the 1917 flood (341,000 ft3/s) occurred in the last ~3,000 years. In addition to flood evidence found in caves and alcoves, flood deposits preserved in exposed stratigraphy at Williams Island, an alluvial island at the head of the gorge, date to ~9,000 years. Determining accurate discharge estimates in this section of the river is difficult due to the backwater from the gorge constriction during high flows, but the flood records preserved here can be used to validate flood evidence downstream in the gorge, where the stable boundary and narrow valley provide more reliable discharge estimates. Stratigraphic records of past floods to reduce uncertainty in flood frequency analyses have been used extensively in the arid western United States, especially for floods with low annual exceedance probabilities. Preliminary results indicate that previously developed techniques to develop stratigraphic records of past floods can be successfully applied to reduce uncertainty in flood frequency analyses in the temperate eastern regions of the United States.

3.3.7.2 Posters

3.3.7.2.1 Probability-Based Flow Modeling Using the Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS) Brian Skahill, U.S. Army Corps of Engineers, Engineer Research and Development Center, Coastal and Hydraulics Laboratory



Probability-Based Flow Modeling Using the Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS)

Risk Informed Hydrologic Analysis

Why Safety Programs Exist

Johnstown, PA
1889
2,200 Dead

St Francis, CA
1928
450 Dead

Canyon Lake, SD
1972
237 Dead $60M

Buffalo Creek, WV
1972
125 Dead & $50M

Teton, ID
1976
11 Dead & $400M

New Orleans, LA
2005
1,800 Dead $100B

Safety Programs Defined

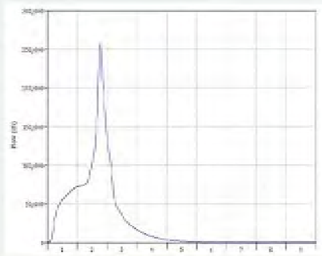
- Art and science to ensure the integrity and viability of dams and levees so they provide benefit to the nation and do not present unacceptable risks to the public, property, and the environment
- Requires a philosophy of risk management
- Includes actions taken to identify or predict deficiencies and consequences and to document, communicate, and manage risk

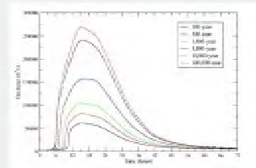
Guiding Principles

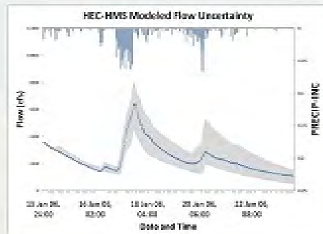
- Life safety is paramount
- Decisions are **risk informed** (consider theory, analysis, observations, experience, judgment, and *uncertainty*)
- Priority, urgency, and level of detail commensurate with the risks and the decisions
- Portfolio risk management
- Do no harm

Changing Needs

Single Design Flood → Range of Hydrologic Hazards with *Uncertainty*







Policy—ER 1110-2-1464,
Hydrologic Analysis of Watershed Runoff

HEC-HMS Development

- With funding from the Flood and Coastal R&D program, a new calibration method has been implemented that explicitly and formally quantifies HEC-HMS model *uncertainty* to support **risk informed** hydrologic modeling
- HEC-HMS model calibration convergence provides multiple likely parameter sets rather than one optimal parameter set
- Its application transforms HEC-HMS from a deterministic to a probability-based hydrologic modeling analysis tool
- It has a documented history of application for search, optimization, and inference with hydrologic models

Optimization Trial | Search | Objective

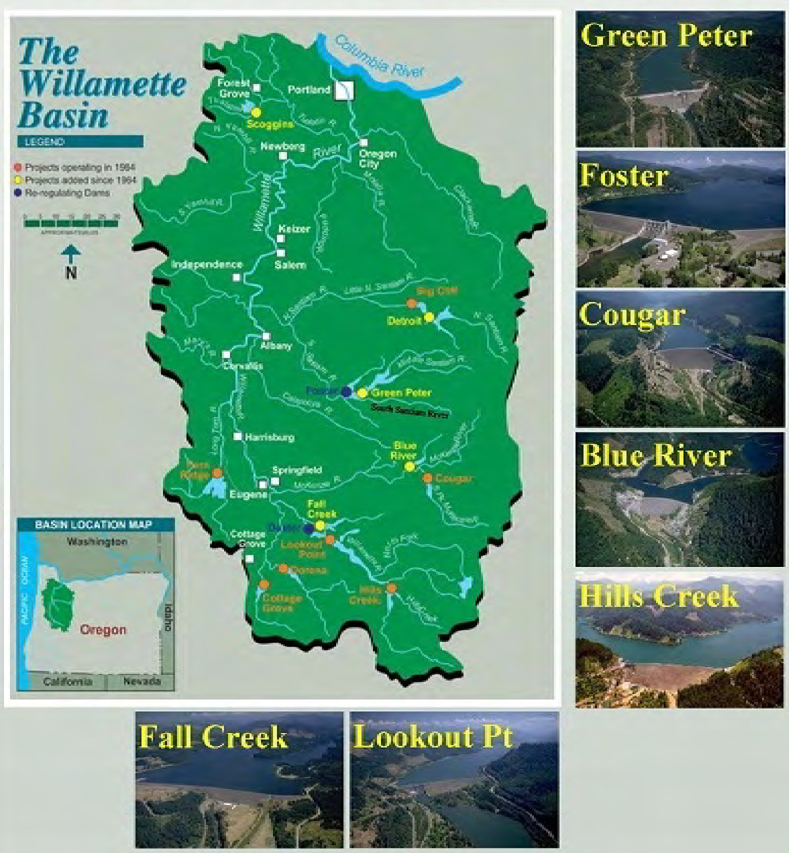
Name: Thomas_CW4
Method: Markov Chain Monte Carlo
*Pool Size: 10
*Initial Sample: 1000
*Min Iterations: 2000
*Max Iterations: 50000
*Convergence: 1.1

Example of Calibrated Realizations from MCMC

Parameter Set	Time of Concent. (hrs)	Storage Coefficient (hrs)	Baseflow Recession	Hydraulic Cond. (in/hr)
1	0.53	6.2	0.212	0.25
2	0.61	5.8	0.231	0.24
3	0.42	5.7	0.222	0.27
4	0.48	5.6	0.223	0.37
....	....	....	....	....
20000	0.58	6.1	0.281	0.21

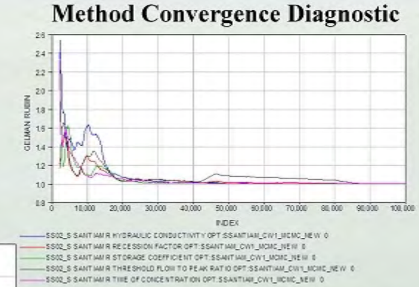
- Several HEC-HMS Basin Model parameters can be selected for the optimization analysis: canopy, surface, loss rate, transform, baseflow, channel routing, reservoir structures
- Parameter sets determined from the optimization analysis can be re-used by the uncertainty analysis
- The uncertainty analysis will randomly select from among the available parameter sets, which preserves correlation between parameters and reduces the chance of unrealistic parameters
- HEC-HMS is integrated within HEC-WAT, which can be used to quantify boundary condition, initial condition, and model parameter uncertainties

Willamette Basin Dam Safety Hydrology



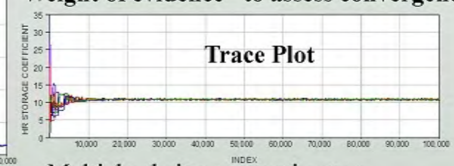
The newly implemented calibration method is being applied to quantify event-specific HEC-HMS rainfall-runoff model parameter uncertainty for select reservoir systems located in the Willamette River Basin (WRB). In the WRB, hydrologic loading curves are being developed at the Green Peter, Foster, Cougar, Blue River, Hills Creek, Lookout Point, and Fall Creek dams, which are undergoing IES Phase II analysis.

Method Convergence Diagnostic

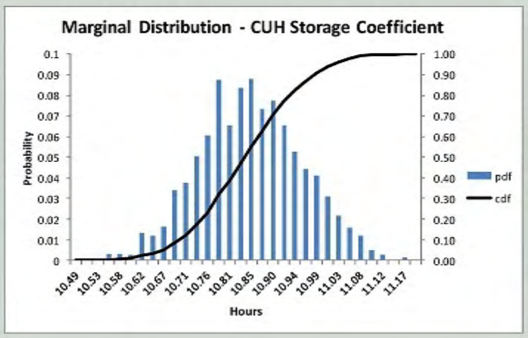


South Santiam River HEC-HMS Model Calibration and Uncertainty Results for calibration to Winter Flood Event 1 (06Feb1996 - 16Feb1996)

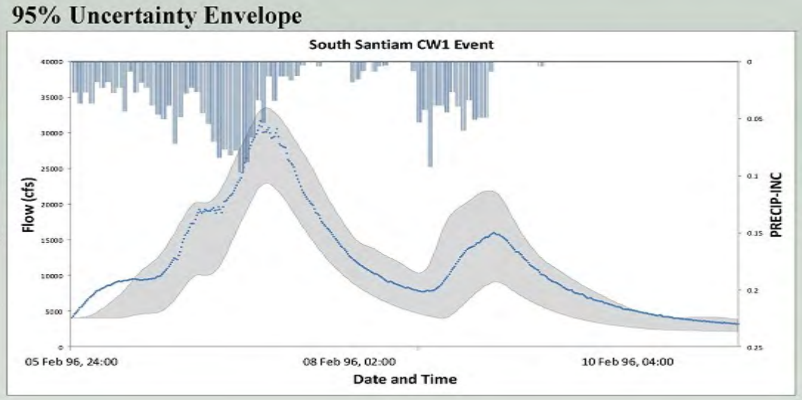
"Weight of evidence" to assess convergence



Multiple chains converging to a reasonable parameter value distribution



95% Uncertainty Envelope



Additional Application Settings

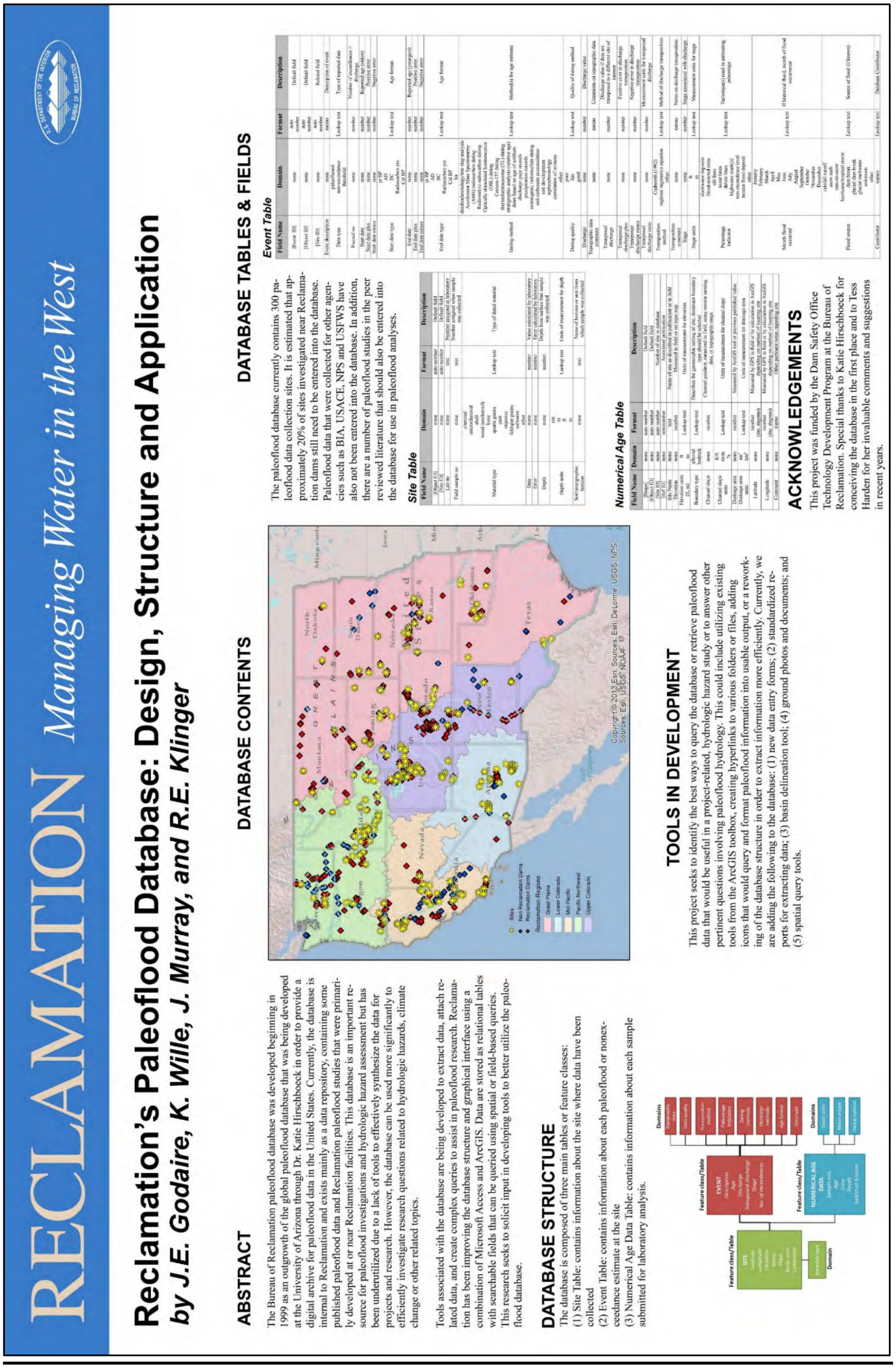
- PMF Uncertainty
- HEC-HMS Model Parameterization Guidance
- N-Year Hydrographs Reflecting Uncertainty for Levee Design and Risk Assessment
- Quantified Parameter Uncertainty in Levee and Dam Stage Frequency Curves

Team: IWR-HEC, ERDC-CHL, USACE-NWP

R&D Needs for Related HEC-HMS Development

Expand current capabilities to support the capacity to (a.) calibrate an HEC-HMS model for a watershed system (i.) using a set of discrete HEC-HMS event model configurations rather than a single event configuration. (ii.) using a set of non-intersecting time intervals for an HEC-HMS continuous simulation run. (b.) include in the objective function/calibration formulation states of the watershed system other than simply flow. (i.) add capability to construct a multi-criteria objective function where the same measurement type processed in different ways comprise separate components of a composite global objective function. (c.) weight observations. (d.) use blended methods for effective and efficient calibration. (e.) use model averaging approaches to account for the uncertainty associated with HMS model choice. (f) pause/stop and restart a calibration run.

3.3.7.2.2 Reclamation's Paleoflood Database: Design, Structure and Application. Jeanne E. Godaire, Kurt Wille, and Ralph E. Klinger, U.S. Bureau of Reclamation, Technical Services Center



Reclamation's Paleoflood Database: Design, Structure and Application

by J.E. Godaire, K. Wille, J. Murray, and R.E. Klinger

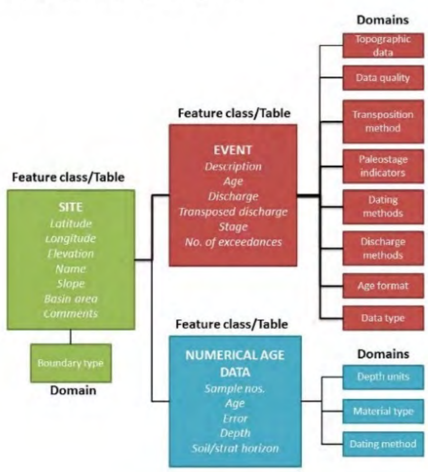
ABSTRACT

The Bureau of Reclamation paleoflood database was developed beginning in 1999 as an outgrowth of the global paleoflood database that was being developed at the University of Arizona through Dr. Katie Hirschboeck in order to provide a digital archive for paleoflood data in the United States. Currently, the database is internal to Reclamation and exists mainly as a data repository, containing some published paleoflood data and Reclamation paleoflood studies that were primarily developed at or near Reclamation facilities. This database is an important resource for paleoflood investigations and hydrologic hazard assessment but has been underutilized due to a lack of tools to effectively synthesize the data for projects and research. However, the database can be used more significantly to efficiently investigate research questions related to hydrologic hazards, climate change or other related topics.

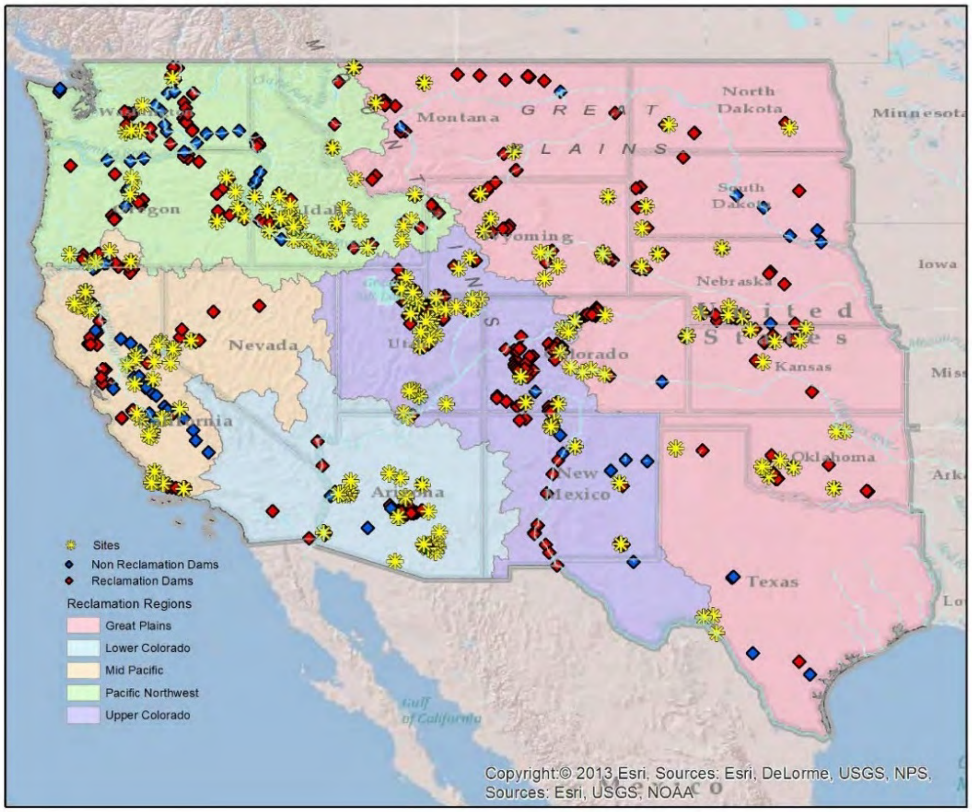
Tools associated with the database are being developed to extract data, attach related data, and create complex queries to assist in paleoflood research. Reclamation has been improving the database structure and graphical interface using a combination of Microsoft Access and ArcGIS. Data are stored as relational tables with searchable fields that can be queried using spatial or field-based queries. This research seeks to solicit input in developing tools to better utilize the paleoflood database.

DATABASE STRUCTURE

The database is composed of three main tables or feature classes:
(1) Site Table: contains information about the site where data have been collected
(2) Event Table: contains information about each paleoflood or nonexceedance estimate at the site
(3) Numerical Age Data Table: contains information about each sample submitted for laboratory analysis.



DATABASE CONTENTS



TOOLS IN DEVELOPMENT

This project seeks to identify the best ways to query the database or retrieve paleoflood data that would be useful in a project-related, hydrologic hazard study or to answer other pertinent questions involving paleoflood hydrology. This could include utilizing existing tools from the ArcGIS toolbox, creating hyperlinks to various folders or files, adding icons that would query and format paleoflood information into usable output, or a reworking of the database structure in order to extract information more efficiently. Currently, we are adding the following to the database: (1) new data entry forms; (2) standardized reports for extracting data; (3) basin delineation tool; (4) ground photos and documents; and (5) spatial query tools.

DATABASE TABLES & FIELDS

The paleoflood database currently contains 300 paleoflood data collection sites. It is estimated that approximately 20% of sites investigated near Reclamation dams still need to be entered into the database. Paleoflood data that were collected for other agencies such as BIA, USACE, NPS and USFWS have also not been entered into the database. In addition, there are a number of paleoflood studies in the peer reviewed literature that should also be entered into the database for use in paleoflood analyses.

Site Table

Field Name	Domain	Format	Description
[Object ID]	none	auto number	Default field
[Site ID]	none	auto number	Default field
Lab no	none	text	Number assigned at laboratory
Field sample no	none	text	Number assigned when sample was collected
Material type	charcoal microcharcoal shell wood (uncharred) bone quartz grains peat organics feldspar grains sediment other	Lookup text	Type of dated material
Date	none	number	Value calculated by laboratory
Error	none	number	Error calculated by laboratory
Depth	none	number	Depth from surface that sample was collected
Depth units	cm in ft m	Lookup text	Units of measurement for depth
Soil/stratigraphic horizon	none	text	Name of horizon or unit from which sample was collected

Numerical Age Table

Field Name	Domain	Format	Description
[Shape]	none	auto number	Default field
[Object ID]	none	auto number	Default field
[Site ID]	none	auto number	Number of site in database
[Ref ID]	none	autonumber	Associated publication
Site Name	none	text	Name of site as described in publication or in field
Elevation	none	number	Measured in field or on topo map
Elevation units (ft, m)	ft m	Lookup text	Units of measurement for elevation
Boundary type	alluvial bedrock	Lookup text	Describes the geomorphic setting of site; dominant boundary type should be selected
Channel slope	none	number	Channel gradient, measured in field, using remote sensing data, or topographic maps
Channel slope units	ft/ft m/m %	Lookup text	Units of measurement for channel slope
Drainage area	none	number	Measured by ArcGIS tool or previous published value
Drainage area units	mi^2 km^2	Lookup text	Units of measurement for drainage area
Latitude	none	number (dec. degrees)	Measured by GPS in field or by calculation in ArcGIS depending on method of locating site
Longitude	none	number (dec. degrees)	Measured by GPS in field or by calculation in ArcGIS depending on method of locating site
Comment	none	memo	Other pertinent notes regarding site

ACKNOWLEDGEMENTS

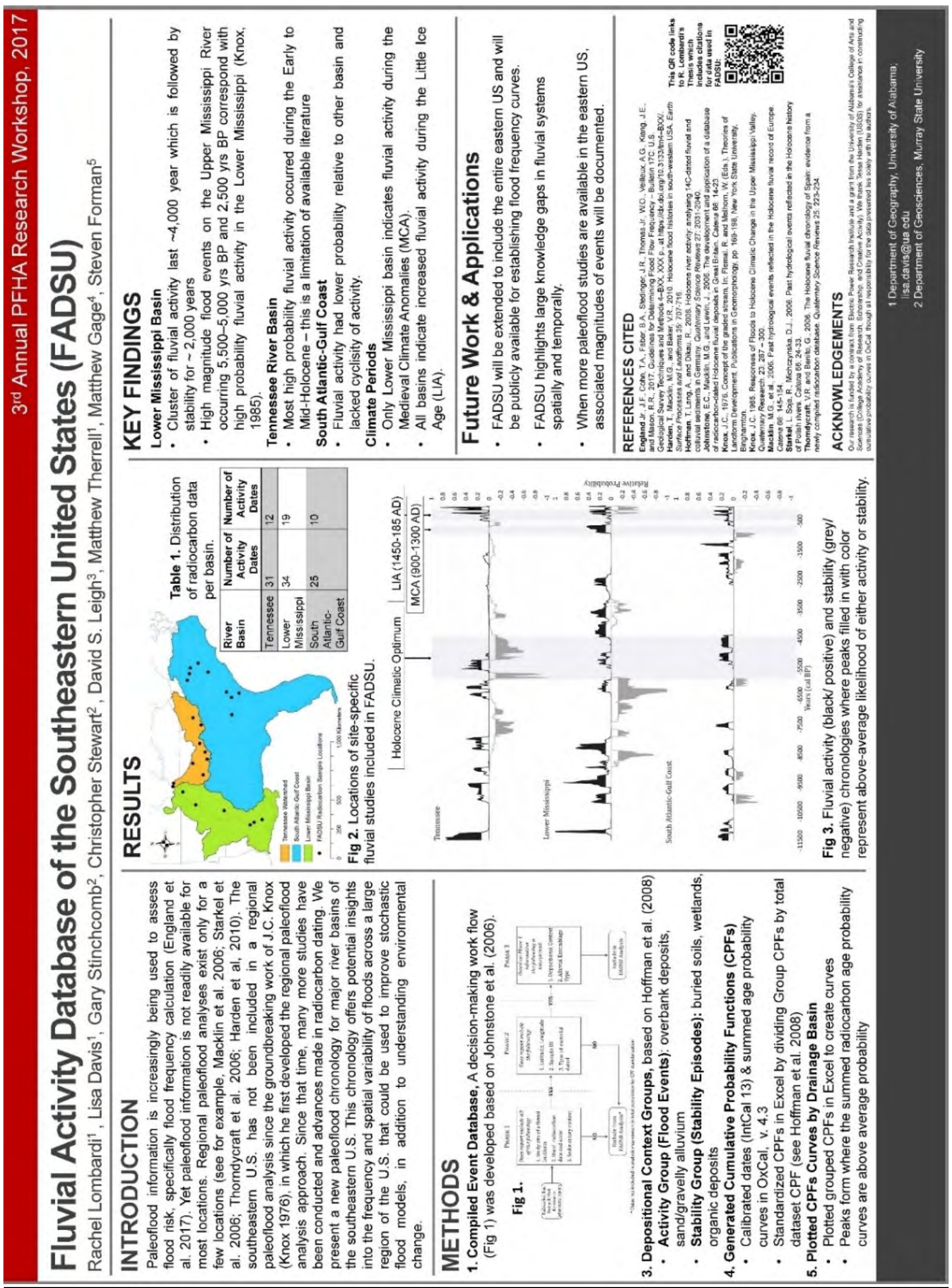
This project was funded by the Dam Safety Office Technology Development Program at the Bureau of Reclamation. Special thanks to Katie Hirschboeck for conceiving the database in the first place and to Tess Harden for her invaluable comments and suggestions in recent years.

Event Table

Field Name	Domain	Format	Description
[Event ID]	none	auto number	Default field
[Object ID]	none	auto number	Default field
[Site ID]	none	auto number	Related field
Event description	none	memo	Description of event
Data type	paleofloood non-exceedance threshold	Lookup text	Type of reported data
Exceed no	none	number	Number of exceedances > discharge
Start date	none	number	Reported age (oldest)
Start date plus	none	number	Positive error
Start date minus	none	number	Negative error
Start date type	yr BP AD BC Radiocarbon yrs Cal BP	Lookup text	Age format
End date	none	number	Reported age (youngest)
End date plus	none	number	Positive error
End date minus	none	number	Negative error
End date type	yr BP AD BC Radiocarbon yrs Cal BP ka	Lookup text	Age format
Dating method	dendrochronology/tree ring analysis Accelerator Mass Spectrometry (AMS) radiocarbon dating Radiometric radiocarbon dating Optically stimulated luminescence (OSL) dating Cesium-137 dating thermoluminescense (TL) dating stratigraphic analysis (relative age) dates based on age of artifacts discharge gage records precipitation records cosmogenic radionuclide dating soil carbonate accumulation soil development tephrochronology correlation of terraces other	Lookup text	Method(s) for age estimate
Dating quality	poor fair good	Lookup text	Quality of dating method
Discharge	none	number	Discharge value
Topographic data comment	none	memo	Comments on topographic data
Transposed discharge	none	number	Discharge value if data are transposed to a different site of interest
Transposed discharge plus	none	number	Positive error in discharge transposition
Transposed discharge minus	none	number	Negative error in discharge transposition
Transposed discharge units	none	number	Measurement units for transposed discharge
Transposition method	Cudworth (1992) regional regression equation other	Lookup text	Method of discharge transposition
Transposition comment	none	memo	Notes on discharge transposition
Stage	none	number	Stage associated with discharge
Stage units	ft m	Lookup text	Measurement units for stage
Paleostage indicator	slackwater deposits flood-scarred trees silt lines scour lines debris lines highwater mark(s) non-exceedance level terrace flood deposit other	Lookup text	Technique(s) used in estimating paleostage
Month flood occurred	January February March April May June July August September October November December	Lookup text	If historical flood, month of flood occurrence
Flood source	rainfall runoff snow melt rain-on-snow hurricane/tropical storm dam break glacial dam break glacial meltwater unknown other	Lookup text	Source of flood (if known)
Contributor	names	Lookup text	Database Contributor

3.3.7.2.3 Late Holocene Paleofloods along the Middle Tennessee River Valley. C. Lance Stewart and Gary E. Stinchcomb, *Department of Geosciences and Watershed Studies Institute, Murray State University*; Steven L. Forman, *Department of Geology, Baylor University*; Lisa Davis and Rachel Lombardi, *Department of Geography, University of Alabama*; Emily Blackaby, Owen Craven and William Hockaday, *Department of Geology, Baylor University*. *Not submitted in these proceedings*

3.3.7.2.4 A regional chronology of floods and river activity during the last 10,000 years in the Eastern U.S Lisa Davis, Rachel Lombardi, Gary Stinchcomb, C. Lance Stewart, Matthew D. Therrell, Matthew Gage*.*



Fluvial Activity Database of the Southeastern United States (FADSU)

Rachel Lombardi[1], Lisa Davis[1], Gary Stinchcomb[2], Christopher Stewart[2], David S. Leigh[3], Matthew Therrell[1], Matthew Gage[4], Steven Forman[5]

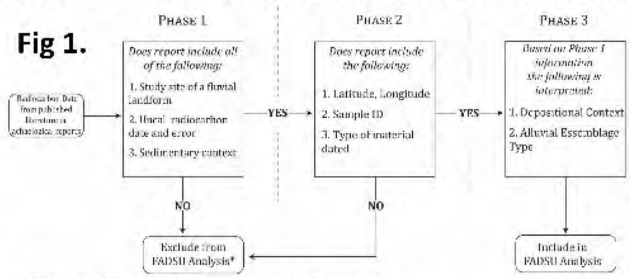
INTRODUCTION

Paleoflood information is increasingly being used to assess flood risk, specifically flood frequency calculation (England et al. 2017). Yet paleoflood information is not readily available for most locations. Regional paleoflood analyses exist only for a few locations (see for example, Macklin et al. 2006; Starkel et al. 2006; Thorndycraft et al. 2006; Harden et al, 2010). The southeastern U.S. has not been included in a regional paleoflood analysis since the groundbreaking work of J.C. Knox (Knox 1976), in which he first developed the regional paleoflood analysis approach. Since that time, many more studies have been conducted and advances made in radiocarbon dating. We present a new paleoflood chronology for major river basins of the southeastern U.S. This chronology offers potential insights into the frequency and spatial variability of floods across a large region of the U.S. that could be used to improve stochastic flood models, in addition to understanding environmental change.

METHODS

1. **Compiled Event Database,** A decision-making work flow (Fig 1) was developed based on Johnstone et al. (2006).

Fig 1.



3. **Depositional Context Groups,** based on Hoffman et al. (2008)
   - **Activity Group (Flood Events)**: overbank deposits, sand/gravelly alluvium
   - **Stability Group (Stability Episodes):** buried soils, wetlands, organic deposits
4. **Generated Cumulative Probability Functions (CPFs)**
   - Calibrated dates (IntCal 13) & summed age probability curves in OxCal, v. 4.3
   - Standardized CPFs in Excel by dividing Group CPFs by total dataset CPF (see Hoffman et al. 2008)
5. **Plotted CPFs Curves by Drainage Basin**
   - Plotted grouped CPFs in Excel to create curves
   - Peaks form where the summed radiocarbon age probability curves are above average probability

RESULTS

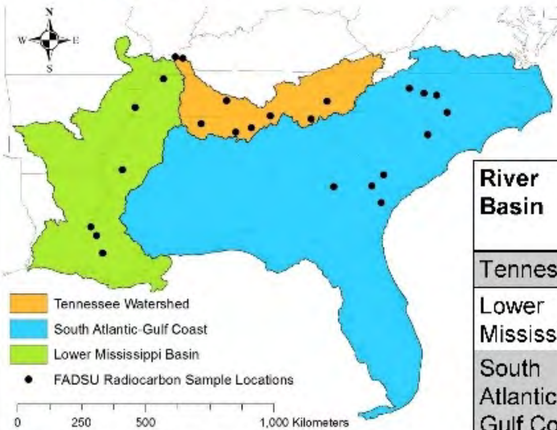


Fig 2. Locations of site-specific fluvial studies included in FADSU.

Table 1. Distribution of radiocarbon data per basin.

River Basin	Number of Activity Dates	Number of Activity Dates
Tennessee	31	12
Lower Mississippi	34	19
South Atlantic-Gulf Coast	25	10

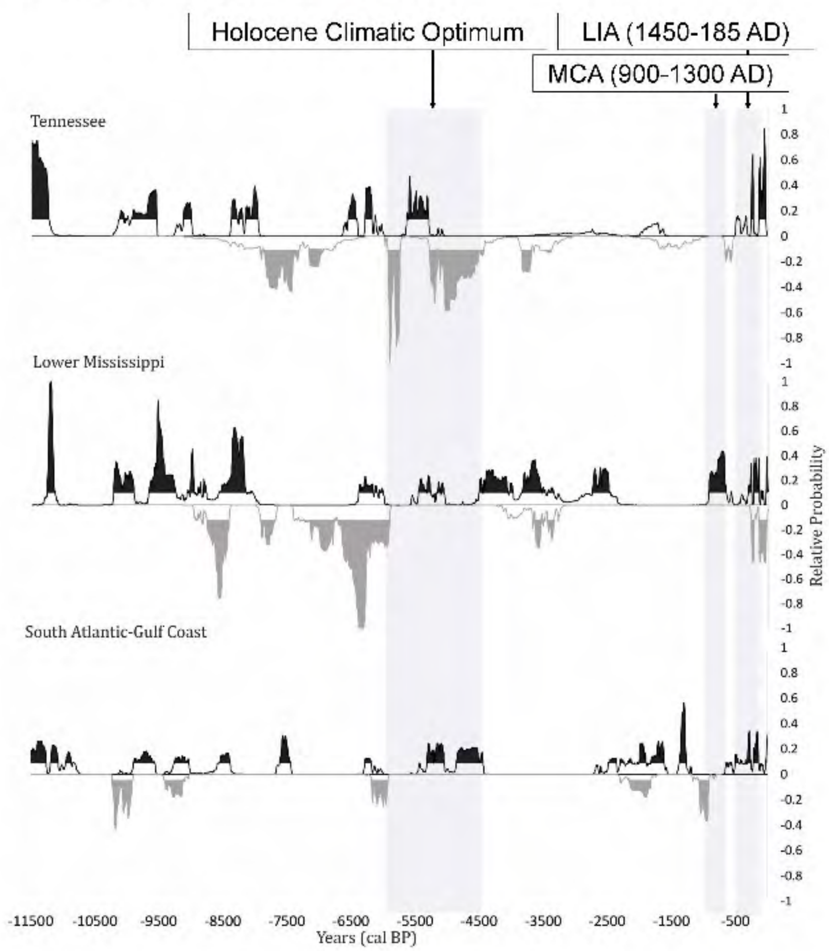


Fig 3. Fluvial activity (black/ positive) and stability (grey/ negative) chronologies where peaks filled in with color represent above-average likelihood of either activity or stability.

KEY FINDINGS

Lower Mississippi Basin

- Cluster of fluvial activity last ~4,000 year which is followed by stability for ~ 2,000 years
- High magnitude flood events on the Upper Mississippi River occurring 5,500–5,000 yrs BP and 2,500 yrs BP correspond with high probability fluvial activity in the Lower Mississippi (Knox, 1985).

Tennessee River Basin

- Most high probability fluvial activity occurred during the Early to Mid-Holocene – this is a limitation of available literature

South Atlantic-Gulf Coast

- Fluvial activity had lower probability relative to other basin and lacked cyclisity of activity.

Climate Periods

- Only Lower Mississippi basin indicates fluvial activity during the Medieval Climate Anomalies (MCA).
- All basins indicate increased fluvial activity during the Little Ice Age (LIA).

Future Work & Applications

- FADSU will be extended to include the entire eastern US and will be publicly available for establishing flood frequency curves.
- FADSU highlights large knowledge gaps in fluvial systems spatially and temporally.
- When more paleoflood studies are available in the eastern US, associated magnitudes of events will be documented.

REFERENCES CITED

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Thorndycraft, V.R. and Benito, G., 2006. The Holocene fluvial chronology of Spain: evidence from a newly compiled radiocarbon database. *Quaternary Science Reviews* 25: 223-234.

This QR code links to R. Lombardi's Thesis which includes citations for data used in FADSU:

ACKNOWLEDGEMENTS

Our research is funded by a contract from Electric Power Research Institute and a grant from the University of Alabama's College of Arts and Sciences (College Academy of Research, Scholarship, and Creative Activity). We thank Tessa Harden (USGS) for assistance in constructing cumulative probability curves in OxCal: though all responsibility for the data presented lies solely with the authors.

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2 Department of Geosciences, Murray State University

3.3.7.2.5 Critical Review of State of Practice in Dam Risk Assessment David Watson, Scott DeNeale, Brennan Smith and Shih-Chieh Kao, Oak Ridge National Laboratory(ORNL); Gregory Baecher, University of Maryland

Critical Review of State of Practice in Dam Risk Assessment

Oak Ridge National Laboratory – David Watson (watsondb@ornl.gov; 865-241-4749), Scott DeNeale, Brennan Smith and Shih-Chieh Kao
University of Maryland – Gregory Baecher
NRC Office of Research – Meredith Carr, Joseph Kanney and Tom Aird

Introduction

Of the large number of dams in the United States, almost 60% are privately owned. About 25 percent are owned by state or local authorities, or public utilities. Only about 5% are owned by federal agencies. The responsibility for dam safety is widely distributed.

Dams in the United States are aging and in dire need of refurbishment. The American Society of Civil Engineers 2017 Infrastructure Report Card states that the average age of the 90,580 U.S. dams is 56 years with 17% classified as high-hazard potential dams with potential for loss of life and another 13% labelled as significant hazard potential dams with potential for significant economic losses. An estimated $45 billion is needed to repair the high-hazard potential dams alone.

Major dams are defined by the US Government as those 50 feet (15 meters) or more in height, with a normal storage capacity greater than 5,000 acre-feet (6 million cubic meters), and a maximum storage capacity of 25,000 acre-feet (31 million cubic meters) or more. The USGS map layer of major US dams comprises 8100 records (USGS 2017).

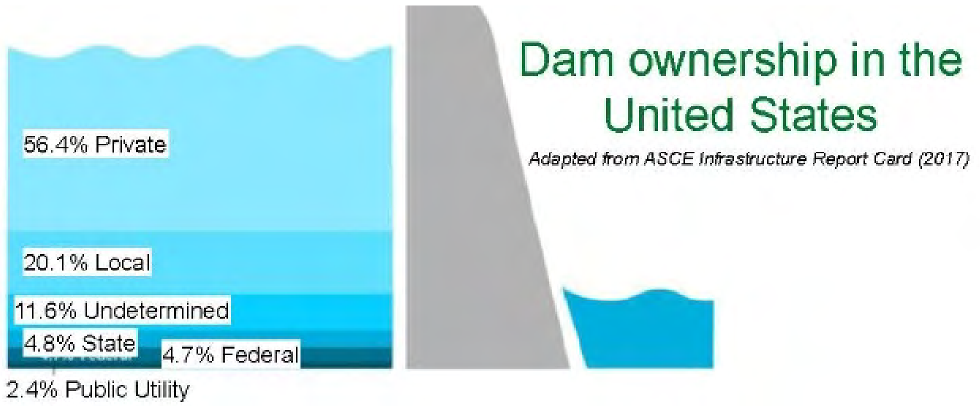
Dams can also pose a risk to the land uses and populations that develop in areas downstream of the dam. If the dam loses containment, downstream property damage can be catastrophic with the potential for loss of life.

Potential detrimental impacts of dam failure include flooding of downstream nuclear power plants and impacts to mine tailing waste disposal facilities.

Agencies involved with dam safety:

- U.S. Department of Agriculture
  - Natural Resources Conservation Service
  - Agriculture Research Service
- Department of Defense
  - Army Corps of Engineers
  - Engineer Research and Development Center
  - Hydrologic Engineering Center (HEC)
- Department of the Interior
  - Bureau of Indian Affairs
  - Bureau of Land Management
  - Bureau of Reclamation
  - Fish & Wildlife Service
  - National Park Service
  - Office of Surface Mining
- Federal Energy Regulatory Commission
- Mine Safety and Health Administration
- International Boundary and Water Commission
- Nuclear Regulatory Commission
- Tennessee Valley Authority
- States

Major dams in the United States (USGS 2017)



Project Objectives

This project will focus on summarizing and providing a critical review of the state of practice in dam failure risk analysis, with a particular emphasis on developing and quantifying fragility information. The objective of this project is to assist NRC in developing the technical basis for guidance on application of state-of-the-practice approaches, methods and tools for dam risk analysis to inform assessment of flood hazards due to dam failure.

This project will seek to summarize and provide a critical review of approaches and methods for developing fragility curves for key components, systems, and procedures that contribute to the overall fragility of the dam. This will include, but not be limited to:

- Probabilistic geotechnical analysis methods for assessing embankment, foundation and abutment stability
- Reliability of key components such as gates, gate hoists, valves, etc.
- Systems analysis approaches
- Reliability of operational and emergency procedures
- Methods for estimating breach initiation and progression

Scope of Work

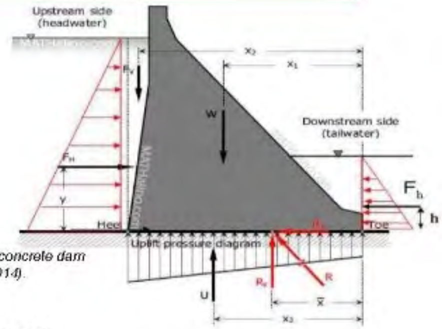
The project will focus on assessing methods for characterizing and quantifying key uncertainties, as well as propagating these uncertainties through the risk analysis procedure to support risk-informed decision-making. To accomplish the objectives of this project the project team will:

1) Assist the NRC in organizing and conducting a workshop to review the current state of practice in dam risk analysis. The workshop participants will include leading experts from other federal agencies, academic researchers and private industry. International perspectives will also be sought.
2) Provide a summary of the current state of practice in dam risk analysis with a particular focus on development of fragility information for key components, control systems, and operational procedures.
3) Provide a critical review of how key process uncertainties, their characterization, and the degree to which they are propagated in state of practice approaches.
4) Prepare NUREG/CR reports summarizing activities 1-3 and providing guidance on use of state-of-practice dam risk assessment approaches, methods and tools for informing assessment of flooding hazards due to dam failure.
5) Conduct a knowledge transfer seminar at the NRC Headquarters in Rockville, MD covering the topics in items 1-4 with a focus on item 3.

Dam Failure Mechanisms

Why Do Dams Fail?

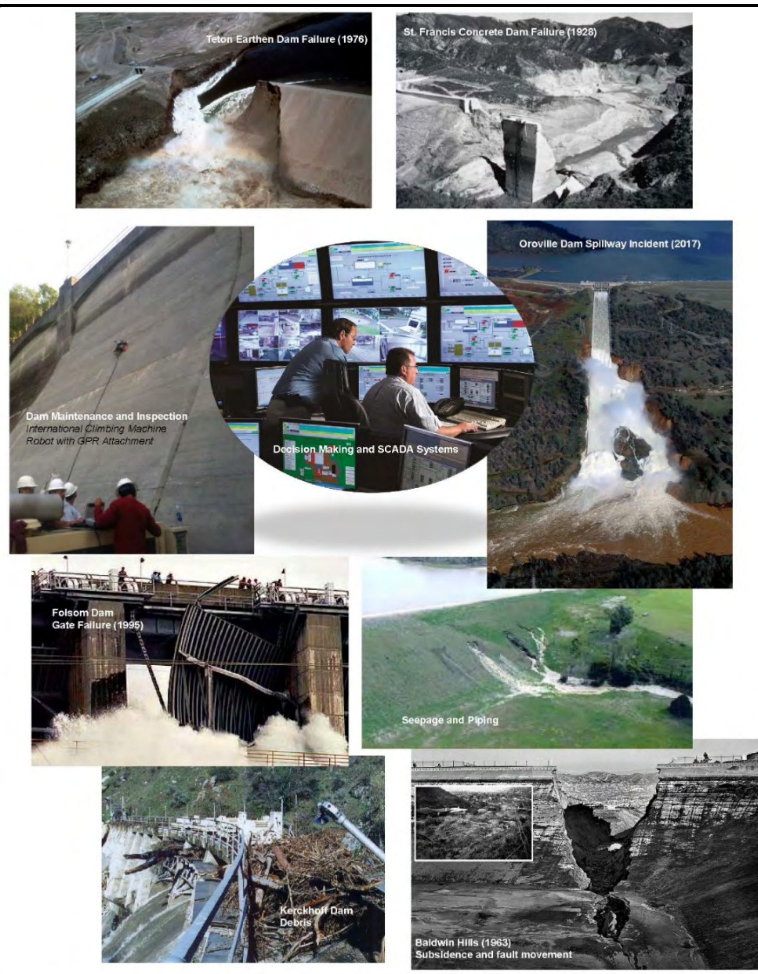
- Overtopping caused by floods that exceed the capacity of the dam
- Overtopping caused by operational issues (gates, human factors, SCADA systems)
- Structural failure of materials used in dam construction
- Movement or failure of the foundation or abutments
- Settlement and cracking of concrete or embankment dams
- Internal erosion of soil in embankment dams
- Inadequate maintenance and upkeep
- Malicious acts



Main loads acting on a concrete dam (Shams Ghahfarokhi 2014).

Causes of dam failure in percent of total from historical data sets.

Mechanism of failure	Gruner 1967	Middlebrooks 1953	Takase 1967	USCOLD 1975	Babb and Mermel 1968
Overtopping or inadequate spillway	23	30	28	38	36
Piping or seepage	40	38	44	44	30
Slides	2	15	10	9	15
Miscellaneous	35	17	18	9	19



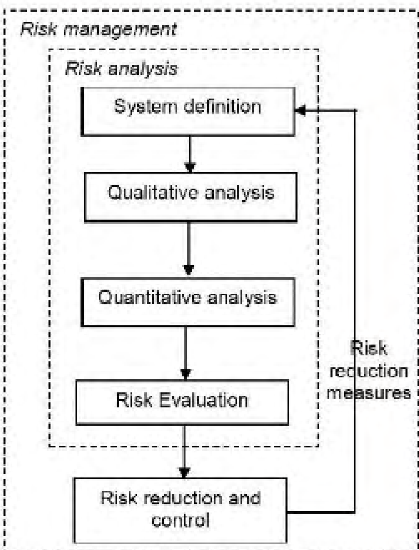
Probabilistic Analysis

Licensees Generally Use Deterministic Methods

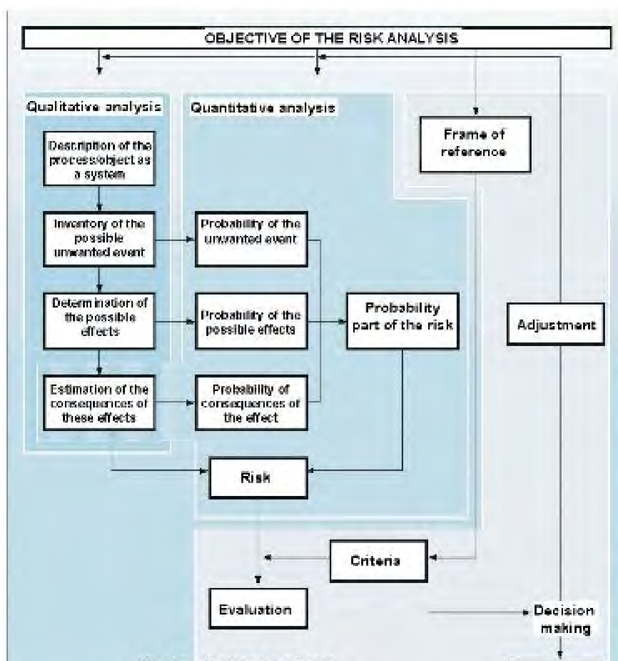
- NUREG/CR-7046 "Design-Basis Flood Estimation for Site Characterization at Nuclear Power Plants in the United States of America" (U.S. NRC 2011)
- Interim Staff Guidance JLD-ISG-13-01 "Guidance for Assessment of Flooding due to Dam Failure" (U.S. NRC 2013)

Risk Analysis Steps

1) Define what "failure" means
2) Identify initiating events
3) Build an event tree of the system
4) Develop models for individual components
5) Identify correlations among component failures or failure modes
6) Assess probabilities and correlations for events, parameters, and processes
7) Calculate system reliability



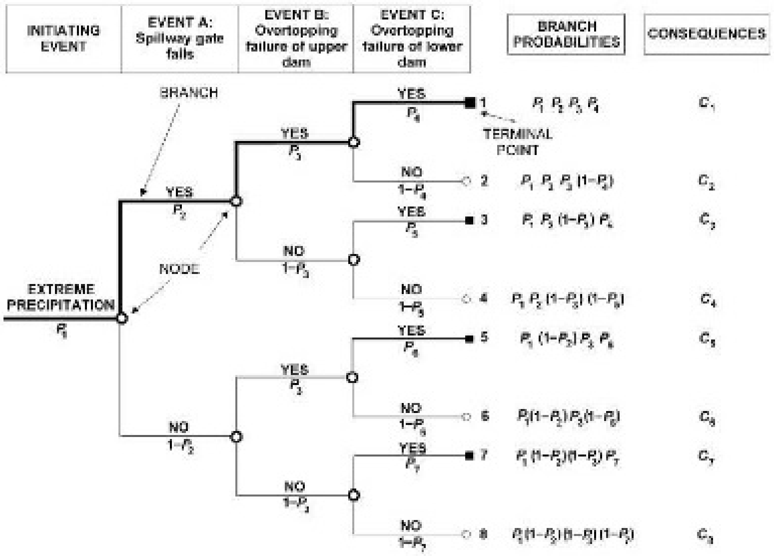
Schematic of risk assessment and management (Jonkman et al. 2015).



Parts of risk analysis
(Adapted from Vrijling and Van Gelder 2002)

Frequency of historical dam failures as reported in the literature

Area	Reference	Number of failures	Dam years 000	Failure rate
US	Gruner 1963, 1967	33	71	8×10^{-4}
	Babb and Mermel 1968	12	43	3×10^{-4}
	USCOLD 1975	74	113	7×10^{-4}
	Mark and Stuart-Alexander 1977	1	4.5	2×10^{-4}
World	Mark and Stuart-Alexander 1977	125	300	4×10^{-4}
	Middlebrooks 1953	9	47	2×10^{-4}
Japan	Takase 1967	1046	30,000	4×10^{-5}
Spain	Gruner 1967	150	235	6×10^{-4}
Overall				4×10^{-4}



Example event tree from Hartford and Baecher (2004)

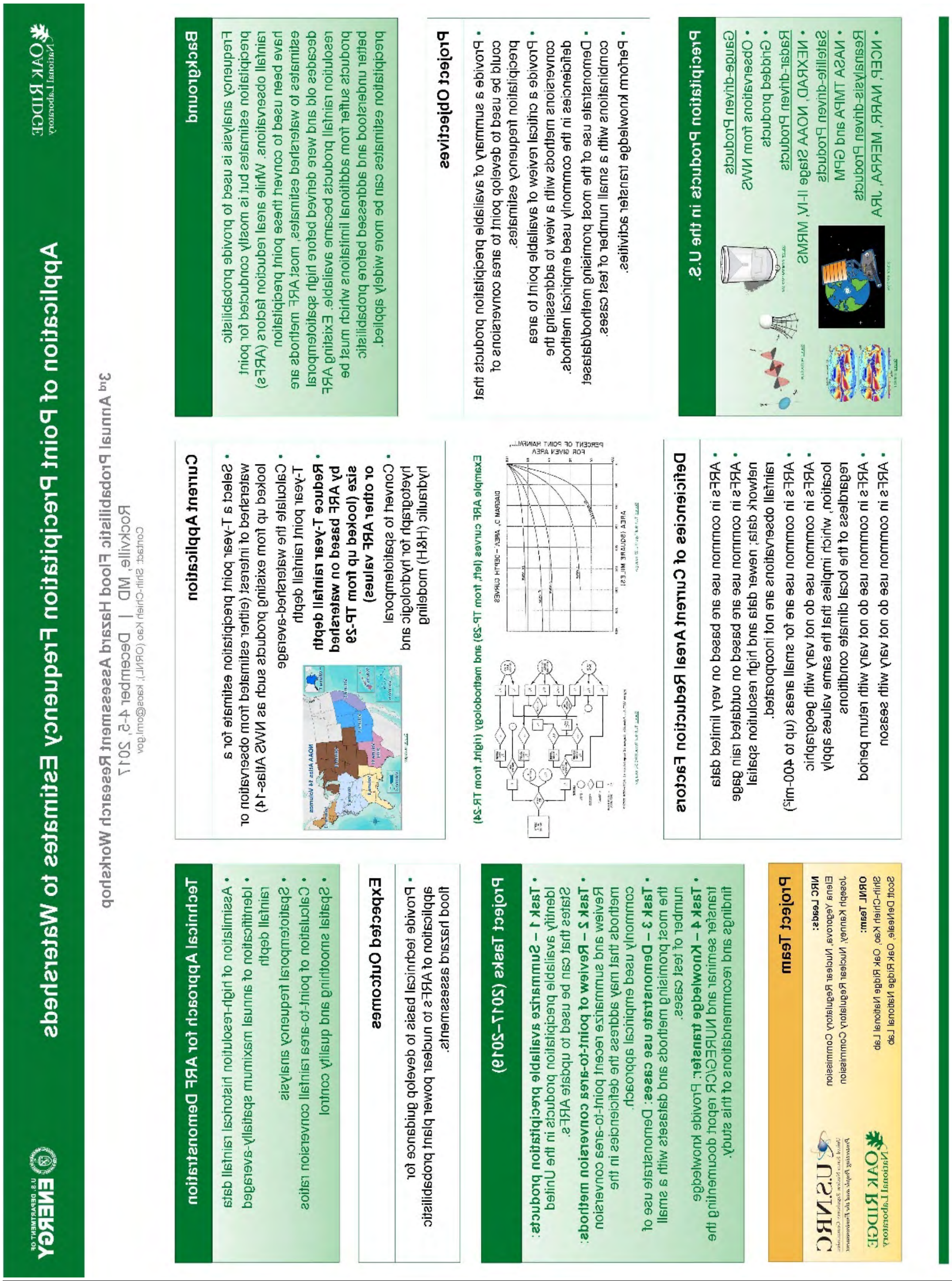
Dam Fragility Analysis Considerations

1) Failure mode identification
2) Event and fault tree analysis and Monte Carlo simulations
3) Failure probabilities, fragility curves and expert opinions
4) Failure progression
5) Systems analysis
6) Regulatory requirements, ownership, maintenance, age, etc.
7) Operational risks, flow control reliability and emergency procedures (Human reliability and SCADA)
8) Software tools for dam safety risk analysis
9) Uncertainties in dam risk analysis

Outcomes

The research conducted under this project will support and enhance NRC's capacity to perform thorough and efficient reviews of license applications and license amendment requests. They will also support risk-informed significance determination of inspection findings, unusual events and other oversight activities.

3.3.7.2.6 Application of Point Precipitation Frequency Estimates to Watersheds Shih-Chieh Kao and Scott DeNeale, Oak Ridge National Laboratory



OAK RIDGE National Laboratory | U.S. DEPARTMENT OF ENERGY

Application of Point Precipitation Frequency Estimates to Watersheds

3rd Annual Probabilistic Flood Hazard Assessment Research Workshop

Rockville, MD | December 4-5, 2017

Contact: Shih-Chieh Kao (ORNL); kaos@ornl.gov

Background

Frequency analysis is used to provide probabilistic precipitation estimates but is mostly conducted for point rainfall observations. While areal reduction factors (ARFs) have been used to convert these point precipitation estimates to watershed estimates, most ARF methods are decades old and were derived before high spatiotemporal resolution rainfall products became available. Existing ARF products suffer from additional limitations which must be better understood and addressed before probabilistic precipitation estimates can be more widely applied.

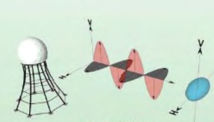
Project Objectives

- Provide a summary of available precipitation products that could be used to develop point to area conversions of precipitation frequency estimates.
- Provide a critical review of available point to area conversions methods with a view to addressing the deficiencies in the commonly used empirical methods.
- Demonstrate use of the most promising method/dataset combinations with a small number of test cases.
- Perform knowledge transfer activities.

Precipitation Products in the U.S.

Gauge-driven Products
- Observations from NWS
- Gridded products

Source: monitorsensors.com



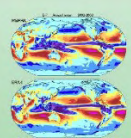
Source: weclipart.com

Radar-driven Products
- NEXRAD, NOAA Stage II-IV, MRMS

Satellite-driven Products
- NASA TMPA and GPM

Reanalysis-driven Products
- NCEP, NARR, MERRA, JRA

Source: nasa.gov



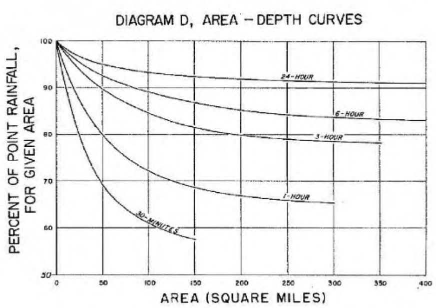
Source: ucar.edu

Current Application

- Select a T-year point precipitation estimate for a watershed of interest (either estimated from observation or looked up from existing products such as NWS Atlas-14)
- Calculate the watershed-average T-year point rainfall depth
- **Reduce T-year rainfall depth by ARF based on watershed size (looked up from TP-29 or other ARF values)**
- Convert to spatiotemporal hyetograph for hydrologic and hydraulic (H&H) modeling

Source: noaa.gov

Example ARF curves (left, from TP-29) and methodology (right, from TR-24)



Source: Technical Paper No. 29, noaa.gov

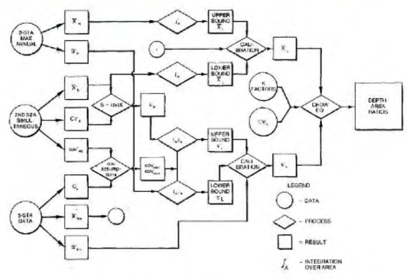


Figure VIII-1.--Schematic diagram of computation of depth-area ratios.

Source: Technical Report NWS 24, noaa.gov

Deficiencies of Current Areal Reduction Factors

- ARFs in common use are based on very limited data
- ARFs in common use are based on outdated rain gage network data; newer data and high resolution spatial rainfall observations are not incorporated.
- ARFs in common use are for small areas (up to 400-mi^2)
- ARFs in common use do not vary with geographic location, which implies that the same values apply regardless of the local climate conditions
- ARFs in common use do not vary with return period
- ARFs in common use do not vary with season

Technical Approach for ARF Demonstration

- Assimilation of high-resolution historical rainfall data
- Identification of annual maximum spatially-averaged rainfall depth
- Spatiotemporal frequency analysis
- Calculation of point-to-area rainfall conversion ratios
- Spatial smoothing and quality control

Expected Outcomes

- Provide technical basis to develop guidance for application of ARFs to nuclear power plant probabilistic flood hazard assessments.

Project Tasks (2017–2019)

- **Task 1 – Summarize available precipitation products**: Identify available precipitation products in the United States that can be used to update ARFs.
- **Task 2 – Review of point-to-area conversion methods**: Review and summarize recent point-to-area conversion methods that may address the deficiencies in the commonly used empirical approach.
- **Task 3 – Demonstrate use cases**: Demonstrate use of the most promising methods and datasets with a small number of test cases.
- **Task 4 – Knowledge transfer**: Provide knowledge transfer seminar and NUREG/CR report documenting the findings and recommendations of this study.

Project Team

NRC Leads:
Elena Yegorova, Nuclear Regulatory Commission
Joseph Kanney, Nuclear Regulatory Commission

ORNL Team:
Shih-Chieh Kao, Oak Ridge National Lab
Scott DeNeale, Oak Ridge National Lab

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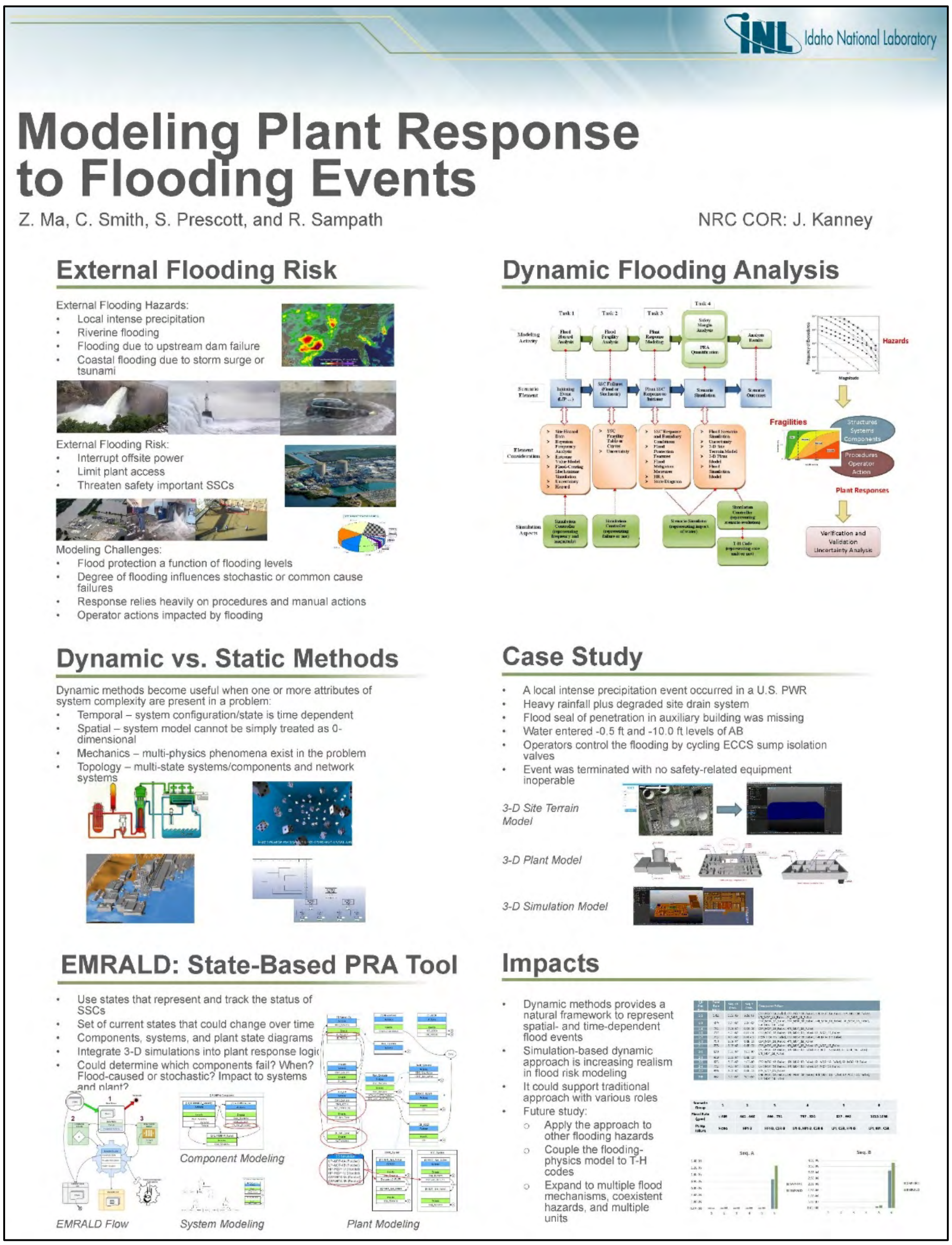
3.3.7.2.7 Quantification of Uncertainty in Probabilistic Storm Surge Models Norberto Nadal-Caraballo, Victor Gonzalez and Efrain Ramos-Santiago, U.S. Army Corps of Engineers, Engineer Research and Development Center, Coastal and Hydraulics Laboratory: *Not submitted for proceedings*

3.3.7.2.8 Modeling Plant Response to Flooding Events Zhegang Ma, Curtis L. Smith and Steven R. Prescott, Idaho National Laboratory, Risk Assessment and Management Services; Ramprasad Sampath, Centroid PIC, Research and Development



Modeling Plant Response to Flooding Events

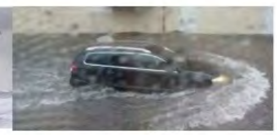
Z. Ma, C. Smith, S. Prescott, and R. Sampath

Idaho National Laboratory

External Flooding Risk

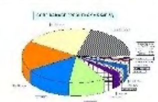
External Flooding Hazards:
- Local intense precipitation
- Riverine flooding
- Flooding due to upstream dam failure
- Coastal flooding due to storm surge or tsunami





External Flooding Risk:
- Interrupt offsite power
- Limit plant access
- Threaten safety important SSCs

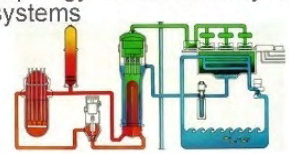
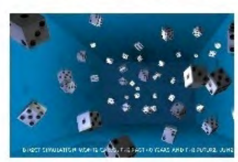


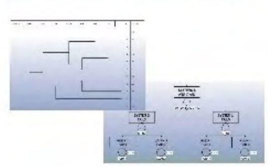



Modeling Challenges:
- Flood protection a function of flooding levels
- Degree of flooding influences stochastic or common cause failures
- Response relies heavily on procedures and manual actions
- Operator actions impacted by flooding

Dynamic vs. Static Methods

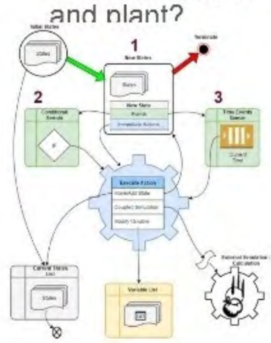
Dynamic methods become useful when one or more attributes of system complexity are present in a problem:
- Temporal – system configuration/state is time dependent
- Spatial – system model cannot be simply treated as 0-dimensional
- Mechanics – multi-physics phenomena exist in the problem
- Topology – multi-state systems/components and network systems

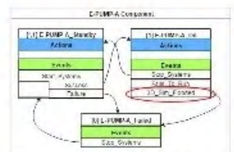


EMRALD: State-Based PRA Tool

- Use states that represent and track the status of SSCs
- Set of current states that could change over time
- Components, systems, and plant state diagrams
- Integrate 3-D simulations into plant response logic
- Could determine which components fail? When? Flood-caused or stochastic? Impact to systems and plant?

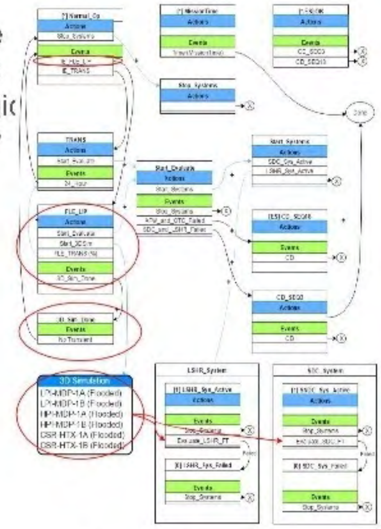


EMRALD Flow



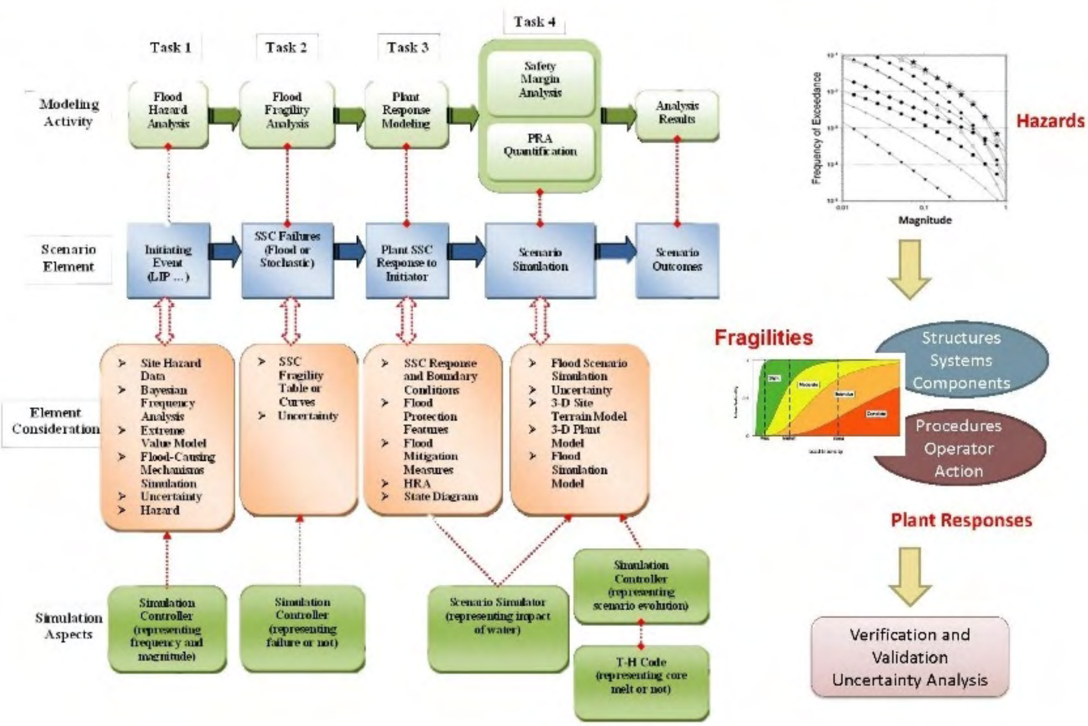
Component Modeling

System Modeling



Plant Modeling

Dynamic Flooding Analysis



Case Study

- A local intense precipitation event occurred in a U.S. PWR
- Heavy rainfall plus degraded site drain system
- Flood seal of penetration in auxiliary building was missing
- Water entered -0.5 ft and -10.0 ft levels of AB
- Operators control the flooding by cycling ECCS sump isolation valves
- Event was terminated with no safety-related equipment inoperable

3-D Site Terrain Model

3-D Plant Model

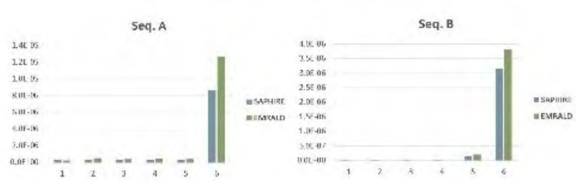
3-D Simulation Model

Impacts

- Dynamic methods provides a natural framework to represent spatial- and time-dependent flood events
- Simulation-based dynamic approach is increasing realism in flood risk modeling
- It could support traditional approach with various roles
- Future study:
  - Apply the approach to other flooding hazards
  - Couple the flooding-physics model to T-H codes
  - Expand to multiple flood mechanisms, coexistent hazards, and multiple units

3-D Sim. Run	Flood Rate (gpm)	Seq. 1B Prob.	Seq. 3 Prob.	Component Failure
1-2	1010	[illegible]	5.5E-06	CSR_MDP_1A_Failed, CSR_MDP_1B_Failed, HPI_MDP_1A_Failed, HPI_MDP_1B_Failed, LPI_MDP_1A_Failed, LPI_MDP_1B_Failed
1-3	[illegible]	[illegible]	[illegible]	CSR_MDP_1A_Failed, CSR_MDP_1B_Failed, HPI_MDP_1B_Failed, HPI_MDP_1A_Failed, LPI_MDP_1B_Failed
1-4	731	7.0E-07	0.0E+00	CSR_MDP_1B_Failed, HPI_MDP_1B_Failed
1-5	[illegible]	[illegible]	0.0E+00	CSR_MDP_1B_Failed, HPI_MDP_1B_Failed, LPI_MDP_1B_Failed
1-7	[illegible]	[illegible]	0.0E+00	[illegible]
1-8	700	2.0E-07	0.0E+00	CSR_MDP_1B_Failed, HPI_MDP_1B_Failed
2-1	705	5.0E-07	0.0E+00	CSR_MDP_1B_Failed, HPI_MDP_1B_Failed, LPI_MDP_1B_Failed
2-2	829	1.0E-07	1.0E-07	[illegible] LPI_MDP_1B_Failed
2-3	600	2.0E-07	0.0E+00	
2-5	875	5.0E-07	1.0E-07	CSR_MDP_1B_Failed, HPI_MDP_1B_Failed, LPI_MDP_1A_Failed, LPI_MDP_1B_Failed
2-6	772	4.0E-07	0.0E+00	CSR_MDP_1B_Failed, HPI_MDP_1B_Failed, LPI_MDP_1B_Failed
2-7	668	5.0E-07	0.0E+00	HPI_MDP_1B_Failed
2-8	992	[illegible]	[illegible]	CSR_MDP_1A_Failed, CSR_MDP_1B_Failed, HPI_MDP_1B_Failed, LPI_MDP_1A_Failed, LPI_MDP_1B_Failed

Scenario Group	1	2	3	4	5	6
Flood Rate (gpm)	< 609	642 - 668	696 - 731	737 - 824	827 - 992	1010-1030
Pump Failure	None	HPI-B	HPI-B, CSR-B	LPI-B, HPI-B, CSR-B	LPI, CSR, HPI-B	LPI, HPI, CSR



3.3.7.2.9 Stratigraphic Records of Paleofloods, Geochronology and Hydraulic Modeling to Improve Flood Frequency Analysis Tessa Harden, U.S. Geological Survey, Oregon Water Science Center- *Not submitted for proceedings*

3.3.8 Day 2: Session 2A - Reliability of Flood Protection and Plant Response I

Session Chair: Mehdi Reisi-Fard, NRC/NRR/DRA

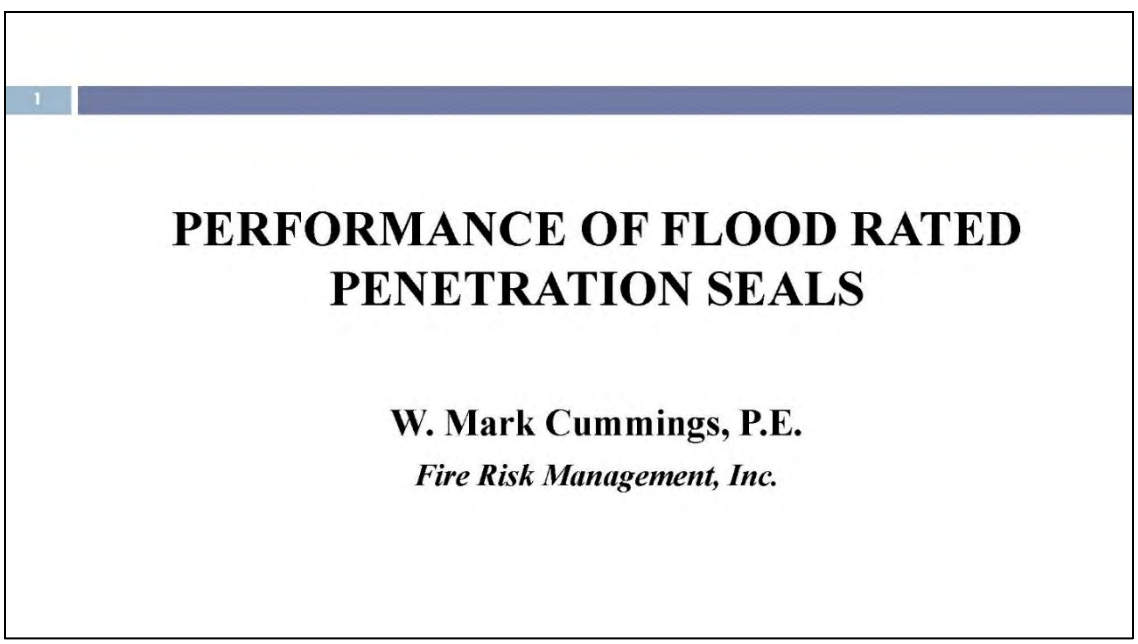
Development of guidance for assessing the reliability of flood protection and plant response to flooding events.

3.3.8.1 Performance of Flood- Rated Penetration Seals William (Mark) Cummings*, P.E., Fire Risk Management, Inc. (Session 2A-1; ADAMS Accession No. ML17355A095)

3.3.8.1.1 Abstract

Overall risk analyses of nuclear power plants (NPPs) include the need for protection against potential flooding events; both internal and external events. Typically, a primary means to mitigate the effects of a flooding event are to construct flood rated barriers to isolate areas of the plant to prevent the intrusion or spread of flood waters. Any penetrations through flood-rated barriers to facilitate piping, cabling, etc. must be properly protected to maintain the flood-resistance of the barrier. Numerous types and configurations of seal assemblies and materials are being used at NPPs to protect penetrations in flood-rated barriers. However, no standardized methods or testing protocols exist to evaluate, verify, or quantify the performance of these, or any newly installed, flood seal assemblies. In FY2016, the NRC implemented a research program to develop a set of standard testing procedures that will be used to evaluate and quantify the performance of any penetration seal assembly that is, or will be, installed in flood rated barriers. This presentation represents a project status update regarding the efforts completed since the previous PFHA Workshop. This includes completion of Phase I of the research effort, which culminated in the development of the draft Test Protocol. Additionally, information is provided regarding plans for Phase II research efforts, which will include actual performance testing of candidate flood-rated penetration seal assemblies using the draft Test Protocol.

3.3.8.1.2 Presentation



Flood Penetration Seal Performance Evaluation

2

NRC PROJECT TITLE: Flood Penetration Seal Performance at NPPs

Project Team: Fire Risk Management, Inc.
Nuvia US

Project Overview:

Project Objective: *To establish Testing Standards and Protocols to evaluate the effectiveness and performance of seals for penetrations in flood rated barriers at NPPs.*

Project Tasks:

Task 1: Development of Testing Standards, Acceptance Criteria, and Protocols

Task 1.1: Identify and describe the various typical seal materials for FPSs used at NPPs

Task 1.2: Develop standard testing procedures, acceptance criteria and protocols for testing effectiveness and performance of FPSs.

Task 2: Testing of Selected Flood Penetration Seal Types and Designs

Task 3: Final Technical Report

Flood Penetration Seal Performance Evaluation

3

TASK 1.1 OVERVIEW

- Researched publicly-available information regarding installed Flood-rated Penetration Seals
  - ADAMS database
  - NPP responses to NRC 50.54 Letter (54)
  - NRC Audit Reports
  - LERs, NUREGs, INs. IRs (relevant info noted in 28/-/15/13)
- Wide variety of seal assemblies and materials noted
  - Concrete, Mortar, Grout
  - Mechanical seals (such as boot or link)
  - Silicone foams (high & low densities)
  - Epoxies & Elastomers
  - Urethane
  - Caulking
- Combination of "fill" materials with exterior "damming" materials applied (waterproofing)

Flood Penetration Seal Performance Evaluation

4

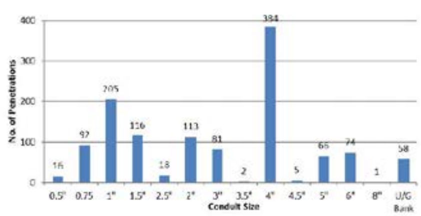
TASK 1.1 OVERVIEW (Cont'd)

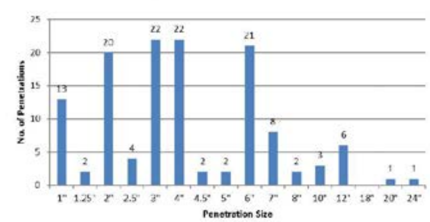
- Wide range of penetration configurations and types of penetrants
  - Rectangular & Circular
  - Sleeved and Core Bore
  - Single & Multiple Penetrants and "Blanks"
  - Pipes, Cables, Conduit, etc.
  - Varying sizes / diameters
- Both interior and exterior applications
- FPS Assessments
  - "Formed in place" seals (foams, elastomers) appear to exhibit greatest variability in performance
  - Materials / Products (formulations) vary between Manufacturers
- Summary Report Developed: "*Flood Penetration Seal Assemblies at Existing Nuclear Power Plants*"

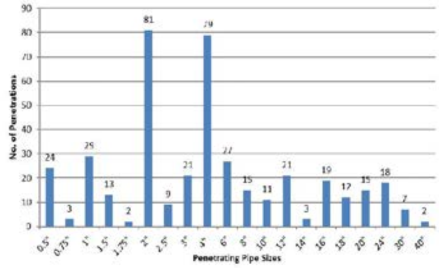
Flood Penetration Seal Performance Evaluation

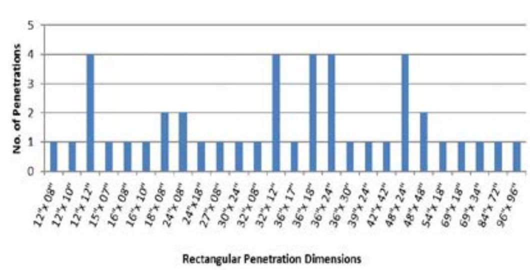
5

TASK 1.1 OVERVIEW (Cont'd)









Flood Penetration Seal Performance Evaluation

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TASK 1.2 OVERVIEW

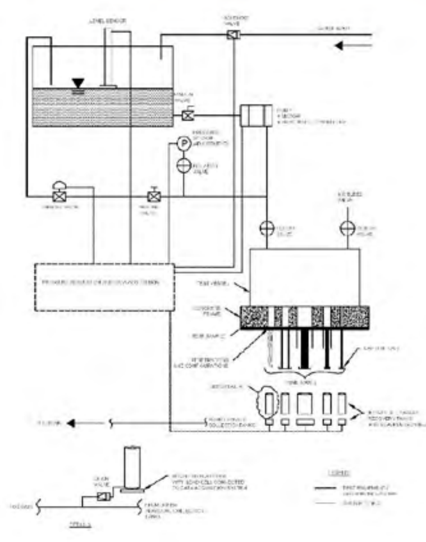
- Review of NUVIA Flood Test Apparatus & Procedures
  - NUVIA is only entity currently testing FPSs; using standard procedures/protocols
- Review of UL 1479 – Fire Tests of Through-Penetration Firestops
  - Section 6A – Water Leakage Test (W rating)
- Review of FM Approval Standard for Flood Abatement Equipment
  - Does not address "penetrations" in flood barriers; primarily the barriers themselves, including dikes
  - Does provide some input regarding "impact" resistance
- Review of ASTM E814 – Standard Test Method for Fire Tests of Penetration Firestop Systems
  - Used as a primary "template" for formatting Flood Test Procedure
  - Industry familiarity with formatting

Flood Penetration Seal Performance Evaluation

7

TASK 1.2 OVERVIEW (Cont'd)

- Development of draft Procedure complete – ready for use in Phase II
  - Provides "guidance" and standardized methodology for testing flood-rated penetration seals
    - Test apparatus design; including data acquisition
    - Performance-based approach to metrics (no specific pass/fail criteria)
  - Manufacturers will need to specify limitations of their products
  - Phase II testing may identify potential short-comings with the p-based approach



Flood Penetration Seal Performance Evaluation

8

TASK 2 OVERVIEW

- Development of Test Plan
  - Selection of candidate FPSs; types and numbers to be tested
  - Final design for Test Apparatus (*completed*)
  - Location for testing (*completed*)
- Test Objective(s)
  - Exercise & evaluate Flood Test Procedure ("test the test")
  - Research/Evaluation of specific FPS assemblies/materials noted as installed at NPPs
- Test Matrix
  - Include all types of seal assemblies & materials
  - Greater emphasis on "formed in place" seals
  - Some evaluation of existing (non-standard) seal configurations noted during Task 1 document research
- Scheduled Test Results/Report due mid-2018
  - Test results used to modify Test Procedure as/if needed
  - Final Test Procedure submitted

Flood Penetration Seal Performance Evaluation

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TASK 3 OVERVIEW

- Development of Final Technical Report
  - Summation of Task 1 & 2 results
  - Suitable for NUREG/CR
- Scheduled Project Completion; 3rd Qtr 2018

GOING FORWARD

- NUREG
  - Provide guidance to Industry for standardized process for evaluating/quantifying FPS performance
  - Support NRC oversight requirements
  - FPS pass/fail criteria will be function of Flood PRA requirements; NPP-specific
- Possible future development of commercial (industry) Test Standard

Flood Penetration Seal Performance Evaluation

FIRE RISK MANAGEMENT

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Presenter Info

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3.3.8.1.3 Questions and Answers

Question:

I'm very interested looking at in situ measurement as opposed to the laboratory… you talked about how you're going to test the seals in laboratory. Have you thought about in situ measurement and looking at performance surrogate indicators for instance moisture content using electric conductivity? Have you thought of how you would go about testing an existing penetration seal?

Answer:

The short answer is no we haven't. Ideally ultimately some particular seals, based on their configuration, their penetrants, may be more conducive to that type than others. If you've been in a lot of cable spreading rooms… trying to run a test like… I don't see how you would do it. Anytime you start introducing moisture, depending on the penetrant they're going to get real nervous about. It hasn't been anything that we've discussed at least not up to this point. It's not really the intent here.

Question:

One last question. At the Blayais site, they had failure with a lot of the penetration seals. Have you been able to talk to Électricité de France (EDF) and found that what kinds of lessons they learned from their failures?

Answer:

We have. A main customer obviously is EDF and so we have looked at that.

Question:

In the proof of the testing, do you intend to increase pressure until the seal fails? Or are you going to pick a design pressure and go to that?

Answer:

The fun part about the research is that you get to play a little bit. Depending on what you see and how things react. We may change but most likely you'll start for each one of the test decks, maybe a step type function. Are we going to go for many hours and days? Probably not. That again gets into the performance of the seals, not so much the test. We're going to play a little bit and look at different pressures.

Question:

I actually have two questions. I had one and then a follow-up to your comment about Blayais site. When you mentioned it was a large penetration… was that a large penetration with multiple penetrants going through it?

Answer:

Yes.

Question:

Then the other question. When you mentioned the exterior and interior seal applications, I was trying to remember back to that report, whether you saw any significant differences in either seal construction, seal types, or sealing material type between those two applications? I don't recall that there was but…

Answer:

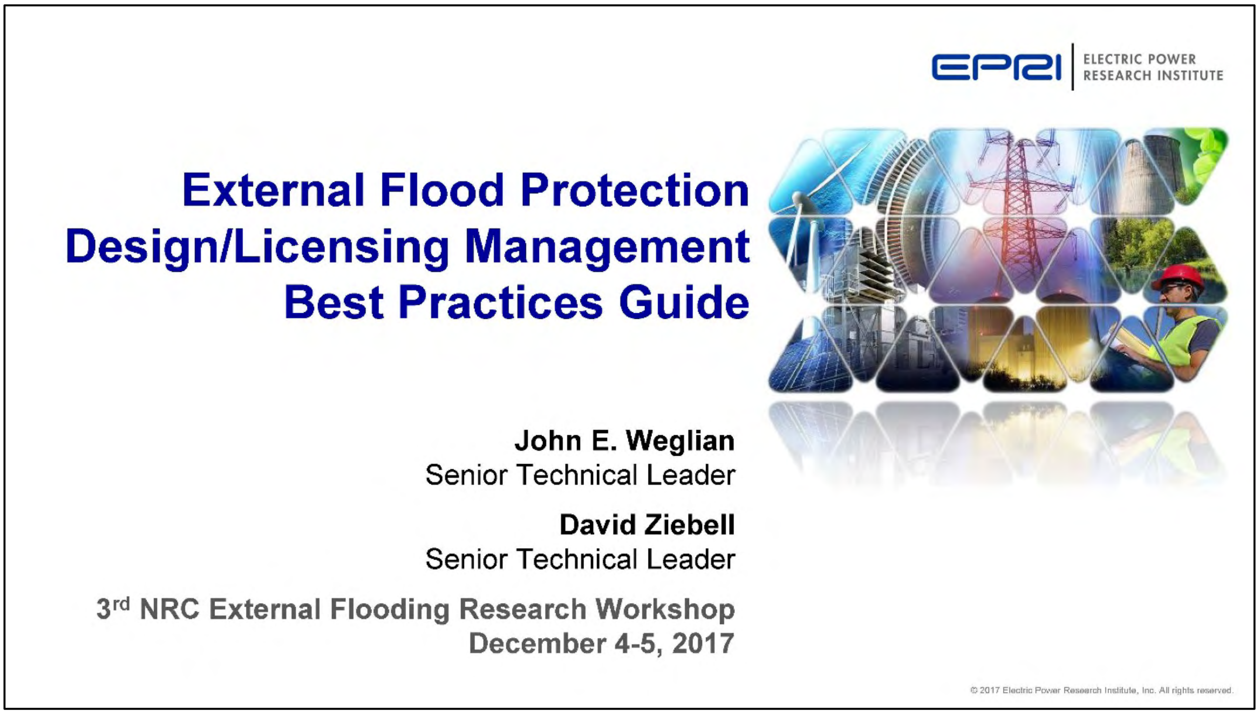
No, there really wasn't and in some of the cases, it didn't actually identify what was an exterior barrier or interior.

3.3.8.2 EPRI Flood Protection Project Status David Ziebell^ and John Weglian*, EPRI (Session 2A-2; ADAMS Accession No. ML17355A096)

3.3.8.2.1 Abstract

EPRI has collected information from member utilities on maintaining the licensing and design bases of flood protection barriers. EPRI and a technical advisory group of industry experts examined this data to determine the best practices in place in the industry. EPRI has recently published these best practices in a guide to EPRI members.

3.3.8.2.2 Presentation



Topics

- EPRI Nuclear Maintenance Applications Center reports
- Technical Advisory Group Membership
- Best Practices Guide Overview

NMAC Reports

- Flood Protection Systems Guide - 3002005423
  - Published in 2015
  - Flood-protection components and the design, testing, inspection, and maintenance of these components
- External Flood Protection Design/License Basis Management Best Practices Guide - 3002010620
  - Published in 2017
  - Practices for owner/operators to assure the day-to-day operation of the plant complies with the design basis and licensing basis with respect to protection of safety functions from external flooding threats.

Technical Advisory Group

Don Bentley	Entergy Operations, Inc.
Joshua Brewer	Duke Energy Carolinas
Karen Carboni	Tennessee Valley Authority
Raymond George	INPO
Jeff Greene	EPRI
Scott Groesbeck	DP Engineering, Ltd. Co.
Sam Harvey	EPRI
Chris Johnson	Entergy Operations, Inc.
John Johnson	Southern Nuclear Operating Co.
Bradley Lanka	Exelon Generation, LLC
Matthew Mairinger	Ontario Power Generation, Inc.

Yasuyuki Moriyama	Chubu Electric Power Co., Inc.
Keita Naito	The Chugoku Electric Power Co., Inc.
Jeffrey Peacock	Exelon Corporation
Frances Pimentel	Nuclear Energy Institute
Swadesh Ramdeen	NextEra Energy, Inc.
Richard Rohrer	Xcel Energy Services, Inc.
Vincent Rougier	Electricite de France S.A.
Denis Shumaker	PSEG Nuclear, LLC
Mark Woodby	Entergy Nuclear Operations, Inc.
Paul Young	Dominion Generation, Inc.
David Ziebell	EPRI

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Best Practices Guide – Section Outlines

- Purpose, Background, Approach and Implementation
- Design Documentation
  - Documenting the design basis external flood event
  - Documenting the flood protection features credited in the design
- Organizational and Procedural Methods
  - Roles and responsibilities
  - Monitoring and responding
- Inspections, Maintenance, and Demonstration of Manual Actions
  - Best practices for inspection for passive flood protection features
  - Best practices for maintenance for active flood protection features
  - Demonstration of manual action effectiveness for flood protection features that require manual action
  - Lessons learned from NEI 12-07 walkdowns

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Best Practices Guide – Section Outlines continued

- Modifications and Work Control
  - Modification impacts
  - Work control
  - Compensatory measures
- Response to Imminent Flooding
  - Severe weather monitoring
  - Proceduralizing external flooding response
  - Recommended elements for external flooding response procedures
- Training and Communication
  - Skills and knowledge
  - Communication

Best Practices Guide – Section Outlines continued

- Management Oversight and Effectiveness Measurements
  - Assessing readiness
  - Assessing capability
  - Corrective action program trending
- References
- Appendix A: General Approach to Development of External Flooding Design and Licensing Bases
- Appendix B: External Flooding Survey Response Initial Analysis
- Appendix C: External Flood Protection Features List Examples
- Appendix D: Reasonable Simulation Timeline

3.3.8.2.3 Questions and Answers

Question:

I assume that by now you've applied this to a variety of sites? Have you? And if you have, what have you discovered, what lessons have you learned in applying these best practices?

Response:

So, the guidance document was just published maybe two or three weeks ago, and I don't know if there have been any lessons learned since it has been published in this short window. But the technical advisory group has been involved to decide what these best practices are and to help inform EPRI to develop this. I don't know if anybody's actually made changes to their plant yet based on this. I can look into that if you would like to know.

Question:

John this looks like a very valuable study here. I'm curious, when it comes to forecast information, for example riverine flood forecasts, you know they're not a high percent accurate. Has there been any discussion about how to deal with that uncertainty in terms of the response?

Response:

That's a good point, and local intense precipitation are quite varied. So, some sites have procedures that are more open to interpretation and others are very deterministic. In that if you get a weather forecast that says “this”, you will implement. I think that is a best practice because it removes the decision and the ability for the operator to make the wrong decision. It removes that possibility based on a judgment call, and so riverine flooding should be similar in that if you know that some sites have procedures that say upstream if you hit this level, you will implement the procedure… as opposed to saying something like if the forecast looks like the site may be inundated, do this. That that would not be a best practice because it leaves room for operator error.

Question:

Is this report publicly available?

Response:

It is not available publicly. It's available to every member or for a price.

Question:

Could you describe a little more detail the forecast? What does the guide say about establishing durable reliable relationships with entities that provide forecasts? Either public entities like The Weather Service, National Hurricane Center, or perhaps a private entity that the licensee might hire? What does the guide say about developing that interface and how to convince yourself that it is durable, reliable?

Response:

Good question. I don't know the exact answer to that… but obviously sites need to establish relationships with the entities that provide this information. Some of it is published on a routine basis like from the national weather service, for example. I can I can look into that and get back to you.

Question:

On the forecast issue. In some cases, there are probabilistic forecasts… National Weather Service for example makes some use of forecasts for the floods. Do you know if there's any thinking about how to handle that kind of probabilistic forecast information?

Response:

I'm not sure if it's treated differently than another set of forecasts. I'd have to look into it and get back to you on that one.

3.3.8.3 A Conceptual Framework to Assess Impacts of Environmental Conditions on Manual Actions for Flood Protection and Mitigation at Nuclear Power Plants Rajiv Prasad *, Ph.D., Garill Coles and Angela Dalton, Pacific Northwest National Laboratory; Kristi Branch and Alvah Bittner, Ph.D., CPE, Bittner and Associates; R. Scott Taylor; Ph.D., Battelle Columbus (Session 2A-3; ADAMS Accession No. ML17355A097)

3.3.8.3.1 Abstract

The U.S. NRC is currently pursuing a Probabilistic Flood Hazard Assessment Research Plan which is especially relevant following the Fukushima accident. One of NRC's initiatives is to better understand the actions that licensees of nuclear power plants have planned to take outside of the control room to prepare for, protect against, and mitigate the effects of flooding events.

The Pacific Northwest National Laboratory (PNNL) conducted a comprehensive review of the literature about how the environmental conditions (ECs) associated with flooding events might affect performance of those actions. To support and inform the literature review, the research team identified and characterized the ECs that might accompany flooding events; these conditions included heat, cold, noise, vibration, lighting, humidity, wind, precipitation, standing and moving water, ice and snowpack, and lightning. Based on a review of (1) NRC Staff Assessments of Flooding Walkdown Reports from 60 nuclear power plant (NPP) sites, (2) available individual NPPs' plant procedures (e.g., Abnormal Operating Procedures), and (3) descriptions of FLEX activities, the research team identified and characterized a set of manual actions (MAs). MAs would need to be performed at and around NPP sites (both inside and outside the main control room) in preparation for or response to a flooding event. The research team developed a method for decomposing the MAs into simpler hierarchical units—tasks, subtasks, generic actions (GAs), and performance demands (PDs)—to facilitate assessment of ECs' impacts consistent with approaches in human performance literature. The first four levels in this hierarchy (i.e., MAs, tasks, subtasks, and GAs) are activity oriented while the last (i.e., PDs) describes the composition of human performance measures needed to accomplish the activities.

The literature review summarized the state of knowledge concerning the effects of the 11 ECs in terms of their mechanisms of action, effects on performance, and potential mitigation measures. A typology of PDs that includes detecting and noticing, understanding, decision-making, action, and teamwork provided a basis for applying research findings to estimate performance effects. PDs include both physical and cognitive aspects of human performance. The research team developed a conceptual framework to illustrate the relationships among ECs, MAs, and performance effects information. ECs can affect human performance by (1) affecting motor functions via a physical force (e.g., flowing water, wind), (2) affecting physiology (e.g., heat, cold), and (3) affecting cognition by interference of senses (e.g., darkness, vibration) and increasing workload. Research on ECs' impacts on human performance in literature is available in four categories: Level 1, quantitative information that is directly applicable to an assessment of impact; Level 2, quantitative information that is less directly applicable; Level 3, qualitative information that may be used to inform expert judgments or sensitivity analyses; and Level 4, no information, i.e., a research gap. The research team demonstrated the applicability of Level 1 information using a simple example of a MA involving gross motor function (i.e., walking). The research team proposed a guideline for safe walking velocity based on experimental data reported in literature. The results show that time to walk a given distance can be significantly affected by the presence of standing and moving water. The research team notes that additional research, sensitivity analyses, and knowledge elicitation from experienced operators may be necessary to operationalize EC effects that fall in Levels 2-4.

3.3.8.3.2 Presentation

Effects of Environmental Factors on Manual Actions for Flood Protection and Mitigation at Nuclear Power Plants

Rajiv Prasad, Garill Coles, Angela Dalton, Nancy Kohn (PNNL)
Scott Taylor (Battelle)
Kristi Branch, Alvah Bittner (Bittner & Associates)

The 3rd Annual Probabilistic Flood Hazard Assessment Workshop
December 4-5, 2017

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Scope and Objectives

- Project scope
  - Review technical literature on effects of environmental conditions (ECs) on human performance
  - An extension of NUREG/CR-5680, The Impact of Environmental Conditions on Human Performance, Volumes 1 and 2 (1994)
  - Consider environmental conditions that could occur during a flood and the manual actions (MAs) taken to prepare/respond
- Research objectives
  - Develop a framework for assessing the impact of ECs on human performance of manual actions for flood protection and mitigation
  - Develop a technical literature review on effects of ECs on human performance
  - Develop a proof-of-concept method for EC impact assessment
  - Identify approaches to using literature review results in the EC impact assessment method

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Characterizing Manual Actions with Performance Demands

- Performance demands are the physical and/or cognitive exertions required by a human operator.
- We developed a taxonomy of performance demands by integrating performance capabilities from NUREG/CR-5680 (Echeverria et al. 1994), taxons (O'Brien et al. 1992), and cognitive functions in NUREG-2114 (Whaley et al. 2013).
- We used performance demands to characterize actions for assessing the impact of ECs on operator performance.

9 Performance Demands

Performance Demands

- **Detecting and Noticing**
- **Understanding**
- **Decision Making**
- **Action – fine motor**
- **Action – gross motor**
- **Action – other neurophysiological functions**
- **Teamwork – reading and writing**
- **Teamwork – oral communication**
- **Teamwork – crew interaction**

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Technical Literature Review on Environmental Conditions

- A key component of the project is the development of a comprehensive technical literature review on ECs pertinent to flood protection and mitigation.
- The literature review updated the information on ECs included in NUREG/CR-5680 and included additional ECs:

1. Vibration
2. Noise
3. Heat
4. Cold
5. Lighting
6. Humidity
7. Wind
8. Precipitation
9. Standing and moving water
10. Ice and snowpack
11. Lightning

11 Environmental Conditions

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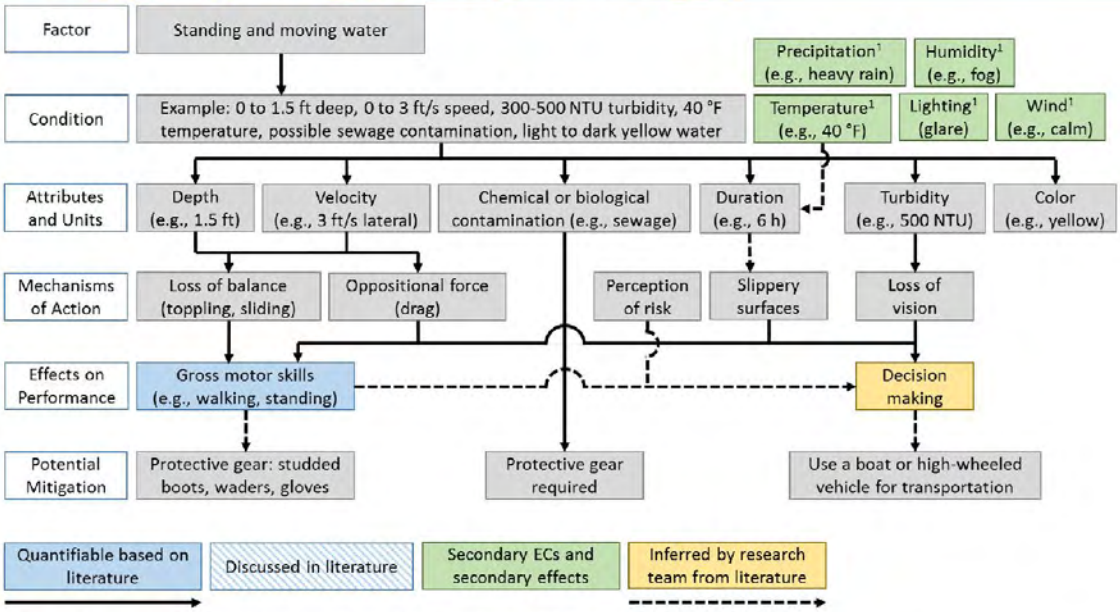
Literature Review Approach: Example of Standing and Moving Water



[1] See cold, heat, precipitation, humidity, lighting, and wind EC figures

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Leveraging Literature Review for Impact Assessment

- Information identified from the literature review was classified into 4 categories in terms of what level of information is available and how it might be used in impact assessment.

Four Levels of Information

1. **Quantitative information that is directly applicable** to determining the quantitative impact of an EC on a performance demand and can be directly used to support the proof-of-concept approach.
2. **Quantitative information** that is of some applicability in determining the degree impact of an EC on a performance demand (e.g., in some cases, EC severity limits may be available - below a lower limit, there is no discernible impact and above an upper limit, an operator cannot perform an activity at all). Under certain assumptions regarding the variation of impacts with changing severity between the two limits, this information might be used with the proof-of-concept model to provide useable information.
3. **Qualitative information**. General agreement exists that the EC affects a performance demand, but the measured impacts are not reported in literature, not even for limits. A performance demand may also be affected because a critical cognitive function is primarily impaired. This information might be used to inform a sensitivity analysis using the proof-of-concept model.
4. **No information** (i.e., a literature gap).

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Example of Literature Review Summary Table – Standing and Moving Water

- For each EC, the available literature was summarized by performance demands and coded based on the 4 levels of information.

Performance Requirements for Standing/Moving Water	Level of Information Related to Impacts	Assumptions and Limitations on Applicability
Detection and Noticing		
Attention, memory, vigilance, switching, acuity, perception and threshold perception	3	(b)
Sensation and visual recognition	3	(b)
Understanding		
Pattern recognition, discrimination, understanding, evaluating, hypothesizing, diagnosing, and integrating	3	(b)
Decision Making		
Reasoning, computation, interpreting, classifying, goal setting, planning, adapting, and evaluating and selecting options	3	(b)
Action		
Fine motor skills - discrete and motor continuous, and manual dexterity	3	(b)
Gross motor skills - heavy and light	1	(a)
Other neurophysiological functions	3	(b)
Teamwork		
Reading and writing	3	(b)
Oral face-to-face and electronic communication	3	(b)
Cooperation, crew interaction, and command and control	3	(b)

- Information levels were not cleanly cut and expert judgment was used to make coding decisions.

1 = Quantitative information that is directly applicable to determining the quantitative impact of an EC on a performance demand and can be directly used to support the proof-of-concept approach.
3 = Qualitative information

(a) Toppling risk is very quantifiable for models, but any individual's toppling tendency may depend on additional factors including fitness, loose or form fitting clothing, shoe gripping abilities, etc.
(b) It can be assumed that once an individual topples in moving water, none of the other manual or cognitive tasks will be possible.

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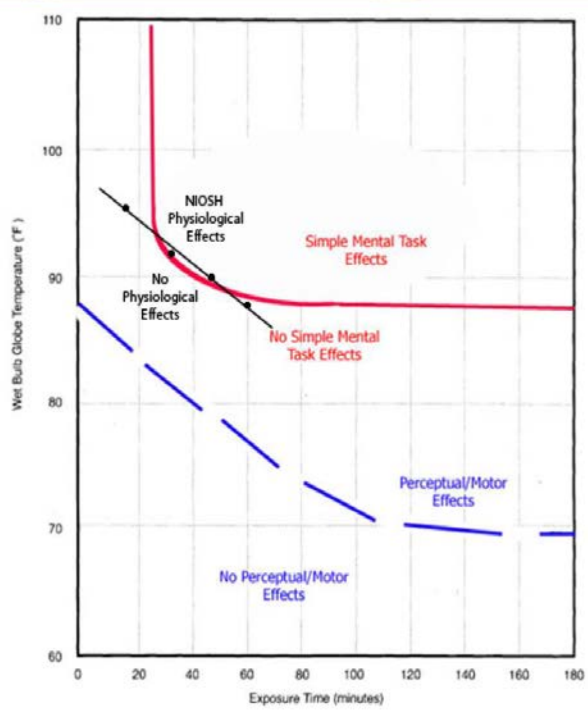
Example of Level 2 EC Information in Literature – Heat



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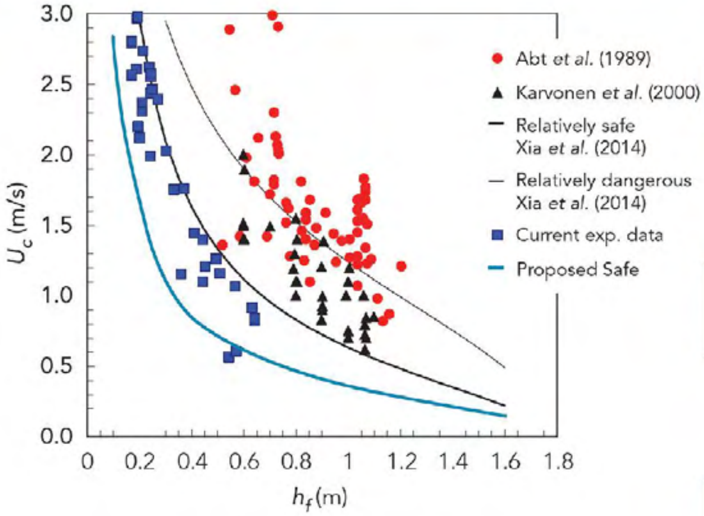
Example of Level 1 Information in Literature – Standing and Moving Water on Human Performance



$$U_c = \alpha \left(\frac{h_f}{h_p}\right)^{\beta} \sqrt{\frac{m_p}{\rho_f h_f^2} - \left(\frac{a_1}{h_p^2} + \frac{b_1}{h_f h_p}\right)(a_2 m_p + b_2)}$$

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h_f is depth of water

h_p is responder height

m_p is responder mass

ρ_f is density of water

α, β, a_1, b_1, a_2, b_2 are constants

Critical flow velocity for toppling, U_c

Safe flow velocity for toppling, U_{ct}= *0.5* U_c

Safe walking velocity *SWV*=max(U_{ct}-*V, 0*)

Example of the Effect of Standing and Moving Water on Human Performance

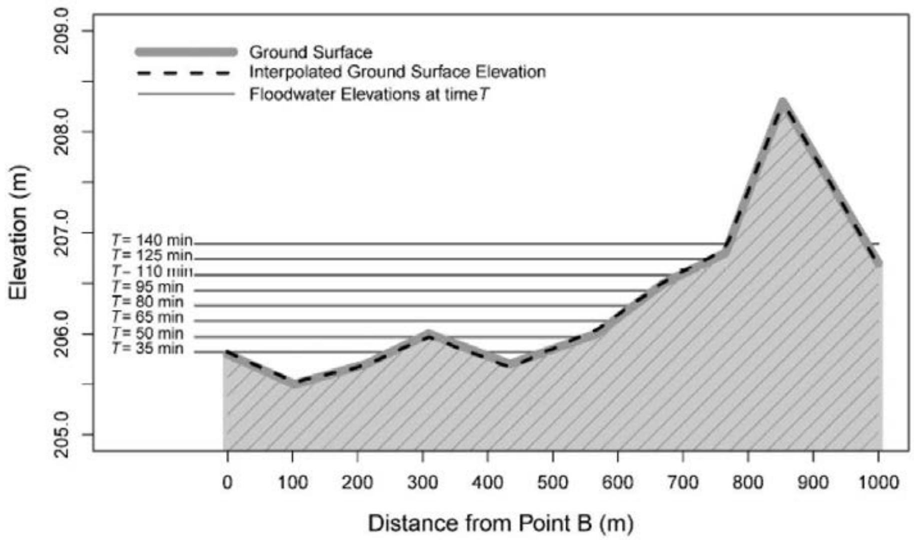
Flood water surface elevation: 204.8 m

Flood water surface elevation: 207.8 m

Distance from Point A to Point B = 1,000 m

ER is triggered when river reaches 205.4 m. Responder's task is to retrieve a piece of equipment from Point B to Point A. The responder is initially at Point A.

Example of the Effect of Standing and Moving Water on Human Performance



$$T_{B-A} = \int_{x_B}^{x_A} \frac{dx}{SWV_x} = \int_{x_B}^{x_A} \frac{dx}{\max\,(U_{ctl} - V_x, 0)}$$

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Timeline of the Example Emergency Action

0:00:00 — ER action is triggered when river reaches 205.4 m (673.8 ft) NAVD88; Responder is at Point A

Responder assembles toolkit and retrieves keys

Baseline walking time

0:20:00 — Responder starts walking from Point A to Point B

Responder walks on dry path

0:32:11 — Responder reaches Point B

Responder isolates and disconnects the equipment

1:12:21 — Responder starts walking from Point B back to Point A

Responder walks on inundated path

1:55:07 1:48:13

Responder walks on dry path

1:58:41 1:51:48 — ER action is completed

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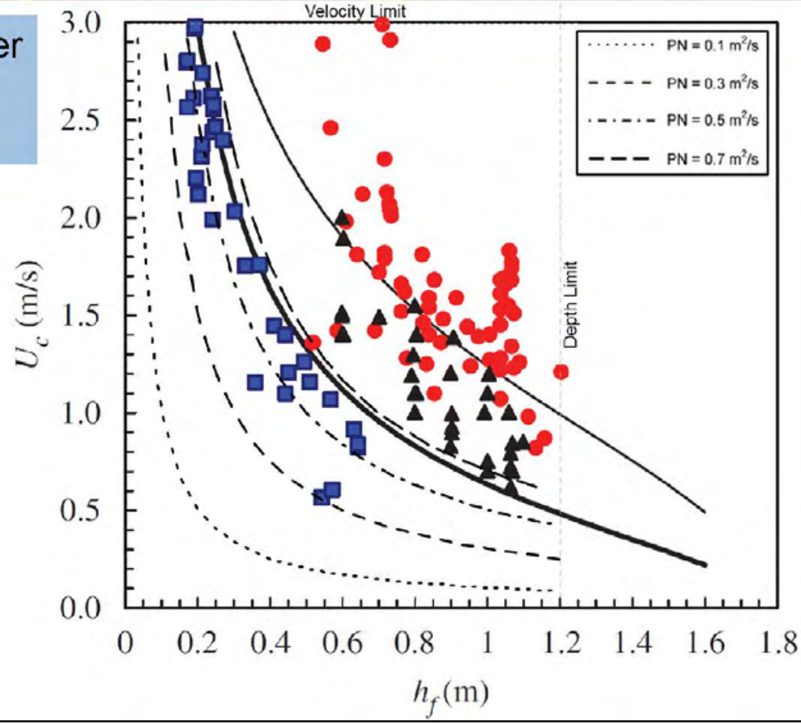
Insights from Reported Experimental Data to Develop a Simple Metric

Product Number

PN = $U_c \times h_f$



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Conclusion

- Existing research findings can be leveraged to provide the technical basis for detailed impact quantification for some ECs based on the research literature
- For walking under flowing water, research suggests that both
  - a rapid evaluation approach (i.e., PN < 0.3) may be used as a simple metric to assess responders' safety
  - a detailed quantitative evaluation on the effect of transit time can be performed using dynamic flood characteristics

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Directions for Future Research

- Adapting the model to account for both primary and secondary EC impacts on performance
- Modeling complexity in task sequence and crew performance
- Expanding the approach to model the time it takes to recover from critical operator errors
- Modeling effects of multiple, simultaneously-occurring ECs
- Modeling the effects of dynamic ECs
- Address uncertainties in model parameters
- Addressing additional factors (e.g., fatigue, stress, and learning) that might influence performance

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Questions?

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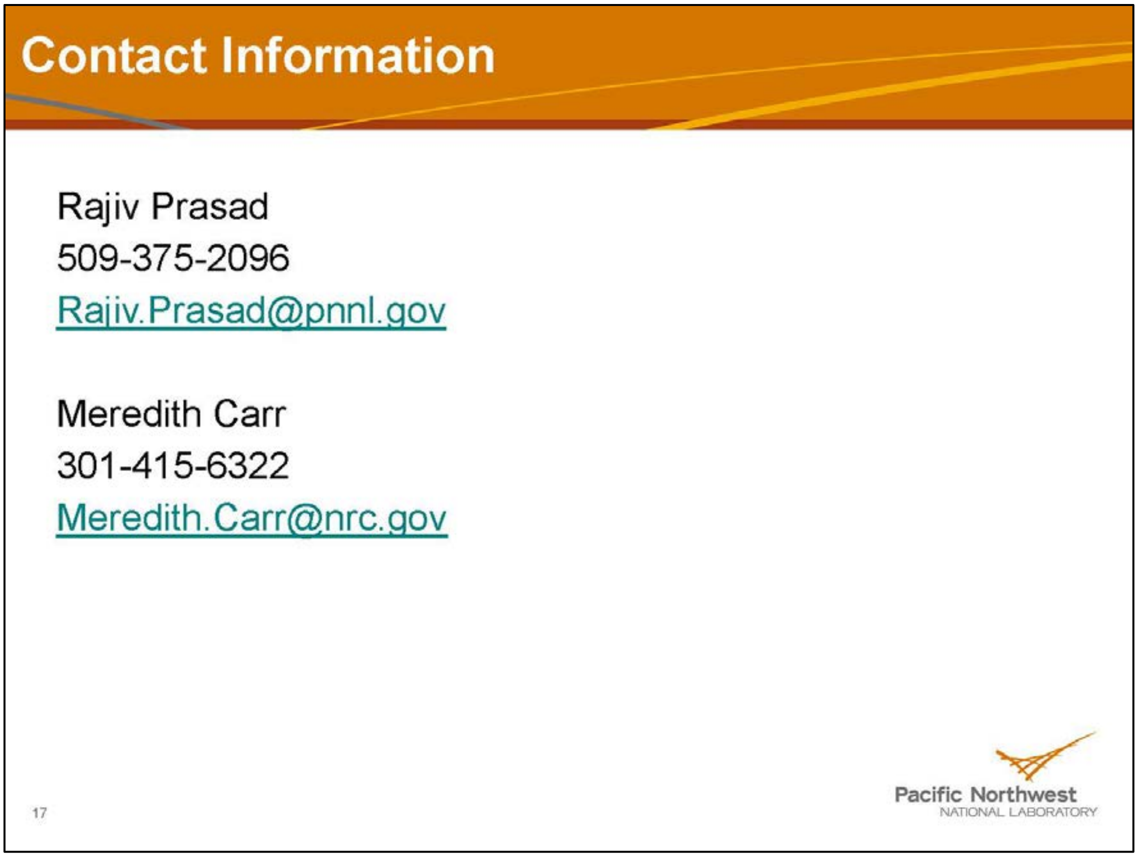


3.3.8.3.3 Questions and Answers

Question:

You mentioned FLEX equipment as part of the consideration, but among the three types of action… I do not find a good match of the FLEX equipment. In particular…the FLEX equipment is portable. What type of action in your design covers this?

Response:

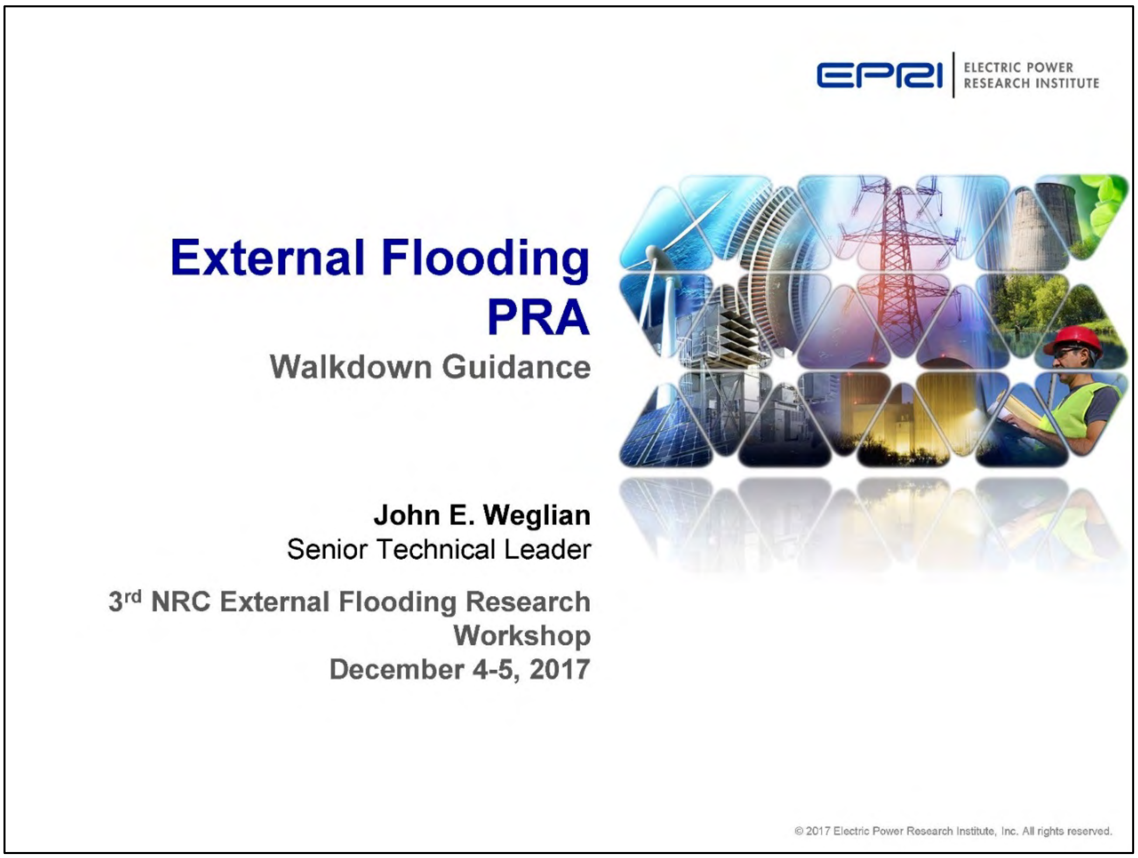
I didn't show you the details of it but the way we think about these manual actions is that we have to do a task analysis to look at what the basic actions might be. And there are these generalized actions that we test… that I talked about… which do involve things like operating a vehicle or moving things from one location to another location that might involve machinery. And using machinery to perform certain tasks, so if you're monitoring things, for example, one of the things that you'll find in the report is an action we described about electrical equipment that needed jumper connections so that is one part of the actions that we're also describing. But when we describe that action, it doesn't really matter what that action is… that is we assume that the personnel that are going to perform these actions are trained in those actions. The only thing that matters is that the human performance itself.

3.3.8.4 External Flooding Walkdown Guidance John Weglian*, EPRI (Session 2A-4; ADAMS Accession No. ML17355A072)

3.3.8.4.1 Abstract

Utilities have performed walkdowns in support of internal flooding PRAs and in response to the 50.54(f) letters from the NRC, they have performed deterministic external flooding walkdowns. However, an external flooding PRA may require something in addition to those two walkdowns. EPRI is conducting research into the requirements for a walkdown to support an External Flooding PRA.

3.3.8.4.2 Presentation



EPRI Research – XFPRA Walkdown Guidance

- External Flooding is a credible hazard to many sites
- An external flooding PRA model can be used to help identify the risks associated with these hazards
- EPRI is conducting research on performing a walkdown to support an external flooding PRA
- A draft guidance report will be available in 2018
- EPRI plans to pilot the guidance prior to publishing the final guidance with lessons learned from the pilot(s)

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External Flooding PRA

- An External Flooding PRA (XFPRA) relies on a number of parts
  - Determine the applicable external flooding hazards to the site
  - Determine the flood parameters for each applicable flood mechanism
  - Develop a flood hazard curve to determine the frequency of the flood parameters
  - Create one or more scenarios that describe relevant portions of the flood hazard curve for each hazard
  - Evaluate the plant response for each scenario with a PRA model and quantify risks associated with each scenario
- For spatially-relevant hazards, plant walkdowns are an important part of a PRA
  - Walkdowns support the determination of the scenarios and evaluation of the plant response

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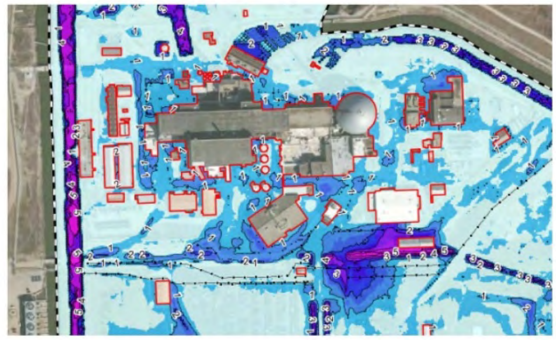
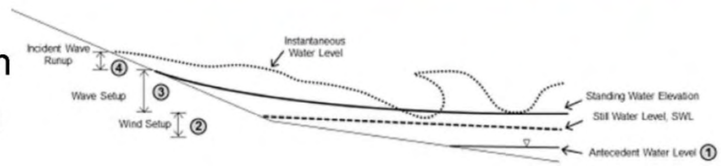
Flood Parameters of Interest

- Stillwater elevation
- Wave run-up elevation
- Hydrodynamic/debris loading
- Sediment deposition or erosion
- Groundwater
- Warning time
- Period of inundation
- Period of recession





Walkdown Focus

- External flooding equipment list (XFEL)
  - A list of the components that could be required to mitigate the event
- External flood operator actions list (XFOAL)
  - Actions personnel take to provide flood protection prior to the arrival of the flood
  - Actions the personnel take after the flood arrives to mitigate the event that may be impacted by the flood
- External flood protection features
  - Barriers to prevent flood waters from affecting plant equipment
  - Sumps or basements that may provide water retention
  - Drainage systems

Leverage Existing Information

- Internal Flooding PRA model
  - SSCs for inclusion in the XFEL including height above the floor
  - Propagation paths for flooding
- Individual Plant Examination of External Events (IPEEE)
  - May provide expected sequence of events for applicable flood mechanisms
  - SSCs for inclusion in XFEL and operator actions in the XFOAL
- Deterministic walkdowns performed for Recommendation 2.3 of the NRC's 50.54(f) letter to utilities
  - Evaluated the site based on deterministic flood parameters for the applicable floods

Leverage Existing Information (cont.)

- Flood Hazard Reevaluation Report (FHRR)
  - Per the NRC 50.54(f) letter under Recommendation 2.1, sites reevaluated their flooding hazards using the current guidance for new reactor sites
  - Includes site topography, important SSCs, and spatial and temporal data relevant to flooding
  - Includes current design and licensing bases flood protection features
- Mitigating Strategies Assessment (MSA)
  - FLEX strategies may have been based on a plant's design/licensing basis flood requirements rather than using the current guidance as was used in the FHRR
  - MSAs demonstrated how the FLEX mitigating strategies could be employed during flooding based on the events evaluated in the FHRR.

Leverage Existing Information (cont.)

- Focused Evaluations or Integrated Assessments
  - Sites with a reevaluated hazard that exceeds the current license bases or design basis were required to submit an integrated assessment to evaluate the plant response to the unbounded flood parameters
  - Following guidance in NEI 16-05, this can take the form of a focused assessment or integrated assessment
  - This report will contain an assessment of flood protection and may include (for the integrated assessments) an analysis of flood hazard frequency

External Flooding Equipment List (XFEL)

- Walkdown team requires certain information on SSCs in the XFEL including:
  - Applicable flood mechanisms that could impact the SSC
  - Location and elevation
  - Normal position and PRA-desired position
- The walkdown would confirm the location and evaluate the SSC's susceptibility to failure from external flooding

External Flood Operator Actions List

- Warning time may provide the ability for operators to take measures to protect against the flood
  - Install flood barriers
  - Build sandbag barriers
  - Movement of portable equipment
- Other actions may be impacted by the flood
  - Increased travel time due to flooding or flood propagation
- The walkdown should confirm that human actions are feasible and determine an appropriate adjustment to timing to perform actions
  - Identify primary and alternate travel paths
  - Confirm materials are available to perform actions
  - Identify any dangers the flooding could present

External Flood Protection Features

- Identify plant features that would protect against flooding including active and passive items such as:
  - Levees
  - Temporary or permanent flood barriers
  - Sump pumps and portable pumps
  - Watertight doors
- Identify features that could retain water
  - Sumps
  - Basements or building levels without important SSCs
- The walkdown should identify important information on the barriers such as:
  - Flood parameters that could defeat the barrier
  - Actions required for active features
  - Retention capability

Next Steps

- Use the Corrective Action Process to address any deficiencies noted during the walkdown
- Create the external flooding scenarios (for example, based on flood height that overtops a levee or other flood barrier)
- Develop propagation of water in the external flooding scenarios to determine which equipment is directly failed by the flood and the time available for human action
- Perform the human reliability analysis to assess the probability of failure of human actions
- Model the external flooding scenarios in a PRA model and assess the risk to the site from the applicable hazards
- Identify any vulnerabilities and determine actions the site can take to reduce those vulnerabilities

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Together…Shaping the Future of Electricity

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3.3.8.4.3 Questions and Answers

Question:

Can you talk about to what degree you're coordinating the development of this guidance with modifications and revisions to the external flooding PRA standards that are currently underway?

Response:

So, we'll be looking at the external flooding PRA standard. This effort is still in draft and we've got like three chapters written so far, but we'll make sure that we're in tune with what's in the standard.

Question:

Do you guys have a library of case histories that can be used for practitioners such that you can learn and describe effects from particular incidents? Say the duration of Fort Calhoun flood and frequency of those events.

Response:

I don't know that we were planning to include that in this document. That sounds more like on the hazard assessment side. To me there's a difference prior to doing the walk down, you do a hazardous assessment, and there's multiple EPRI guidance documents that tell you how to do that. That sets the stage if you will for what the site will look like and those should include certainly those lessons learned. Then you would incorporate that into your information when doing the walk down.

Question:

Let me rephrase. Were there lessons learned on the walk down post-event for Fort Calhoun that could be used to inform that guidance?

Response:

Obviously, their duration was three months or so…

Other Response:

Their assumptions on the PMF and dam failures are on the order two to seven days so there's a disconnect between the frequency of events and what can happen and vulnerabilities for the response. That's what I'm highlighting here, so this could be a neat opportunity to synthesize those case histories to improve the lockdowns and responses.

Response:

That's a good point. I'll take that into consideration.

Question:

Nathan Siu, [NRC] Office of Research. The IPEEE's are really old studies…your last slide talked about updating the plant PRA to include external flooding. If you're going to update your analysis to include external flooding, it states: here's what we would suggest you do?

Response:

No. I'm assuming that you're not going to do a walk down unless you're building a PRA. If you've decided that you're screening out all the hazards or your hazard risk is low enough through some analysis that you don't require an actual PRA model, then you wouldn't be in this step. Now to the last point… these next steps are after you've done the walk down so this is after the guidance.

3.3.8.5 Erosion Testing of Zoned Rockfill Embankments Tony Wahl^, Hydraulics Laboratory, Denver, Colorado, U.S. Bureau of Reclamation (Session 2A-5; ADAMS Accession No. ML17355A073)

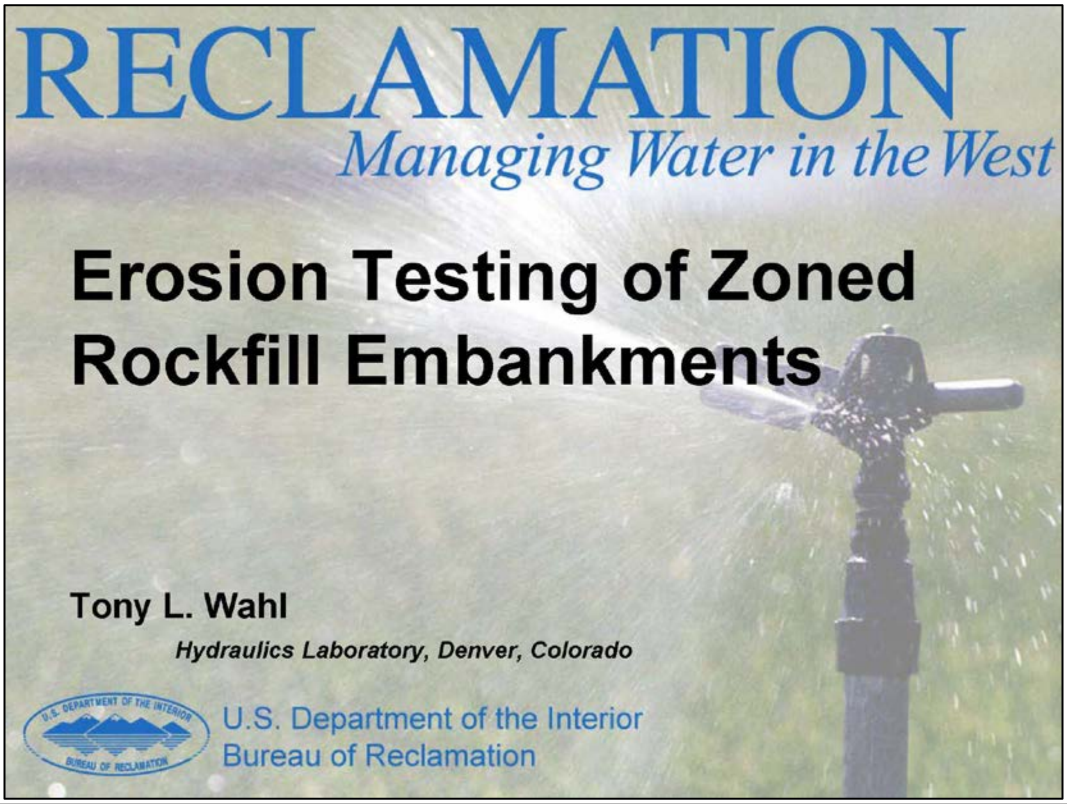
3.3.8.5.1 Abstract

Three medium-scale embankment dam breach experiments (3-ft dam height) were recently performed by the Bureau of Reclamation. The first test was of a homogeneous silty clay embankment failed by internal erosion through an intentionally created concentrated leak. Two subsequent tests funded by NRC considered zoned embankments with a silty clay core sandwiched between upstream and downstream rockfill zones modeled with a well graded road base soil having 12% fines. One of these embankments was failed by overtopping flow and the second was subjected to internal erosion in a manner similar to the test of the homogeneous silty clay embankment.

In the overtopping test of the zoned embankment, the downstream rockfill zone demonstrated significant erosion resistance. The pattern of breach development was characterized by surface erosion of the downstream slope and the top of the exposed silty clay core, which is in contrast with the headcut erosion that is often observed in cohesive soils. Photographic records were used to evaluate rates of erosion and to estimate applied stresses and erodibility parameters for the rockfill zone, which seemed to be the primary control on the rate of breach development. Estimates of erodibility parameters were compared to results of submerged jet erosion tests. The contribution of gravel to the erosion resistance of the well graded soil was very significant.

The internal erosion tests demonstrated the dramatic influence of upstream and downstream gravel zones on the internal erosion breach development process. Initially, the gravel zone acted as a filter and was able to heal the concentrated leak through the core. After the concentrated leak was enlarged, the gravel zones acted to limit the flow, which significantly slowed the development of internal erosion. Observations from the tests are discussed and compared to available numerical and empirical models that can be used to evaluate the risk of internal erosion.

3.3.8.5.2 Presentation



Overview

- Three dam breach tests 2015-2017
  - First test funded by Reclamation Dam Safety
    - Homogeneous silty clay soil (CL-ML), internal erosion
    - Baseline for subsequent tests, same soil later used as core of zoned embankments
  - NRC-funded tests
    - Zoned embankment – overtopping
    - Zoned embankment – internal erosion

2

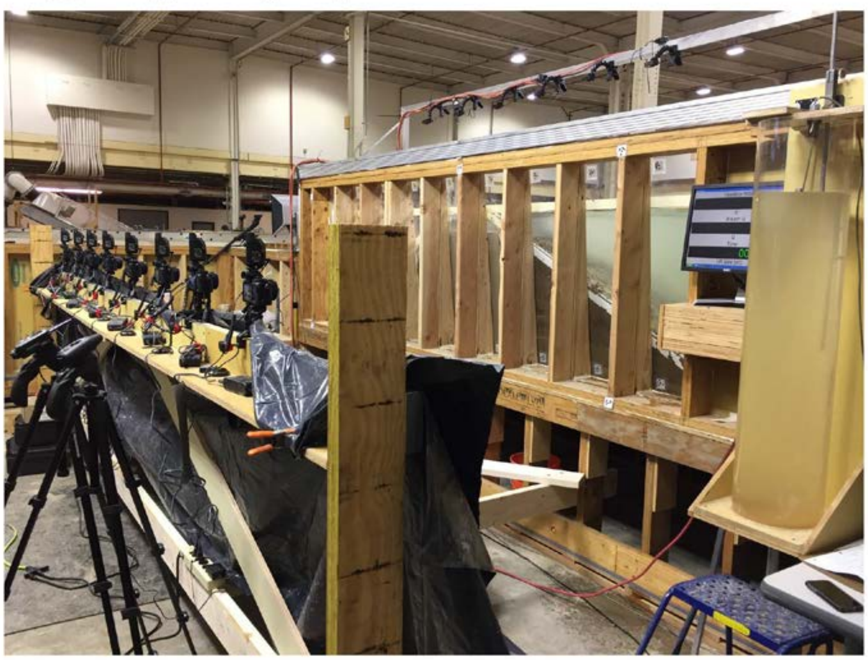
Dam Breach Test Facility

Denver, Colorado

- 13-ft wide, 3-ft high embankment
- Inclined abutment (1:10), acrylic for viewing
- Large tailbox to contain breach outflow
- Headbox spillway with adjustable crest to maintain steady reservoir level

3

Imaging Equipment



Objectives

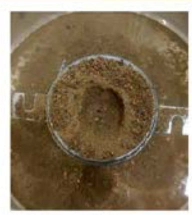
Observe erosion and breach development mechanics, compare to numerical models

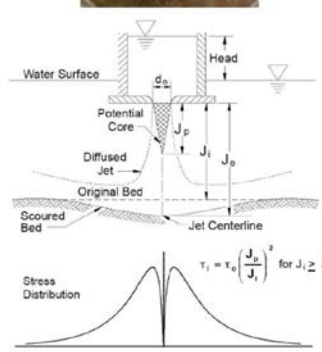
Materials

- Establish erodibility parameters of soils
- Demonstrate consistent relationships between applied stress, erosion resistance, and observed erosion

$$\varepsilon_r = k_d \ (\tau - \tau_c)$$

Submerged Jet Test - Erodibility





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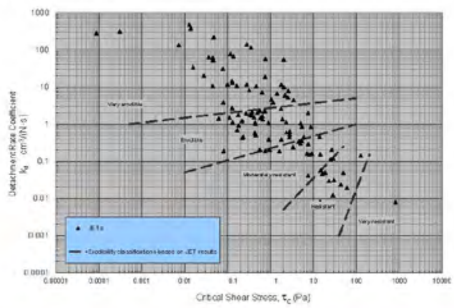
Erodibility varies widely

- **Hanson and Simon (2001) study of streambed soils**
- **USBR studies of remolded soils**



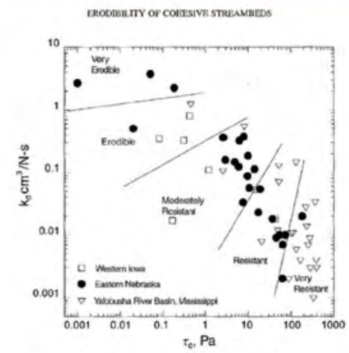


Figure 8. τ_c versus k_d from cohesive streambed tests

Jet test was developed primarily for cohesive soils

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Test 1

- **Homogeneous embankment of Silty Clay (CL-ML), internal erosion triggered at mid-depth by withdrawing 0.5-inch rebar**
- **k_d=5.5 ft/hr/psf τ_c=0.0015 psf (from pre-test JETs) (Very erodible)**

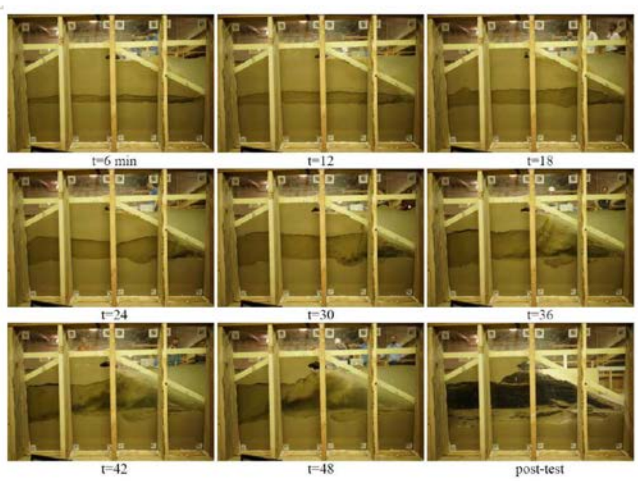
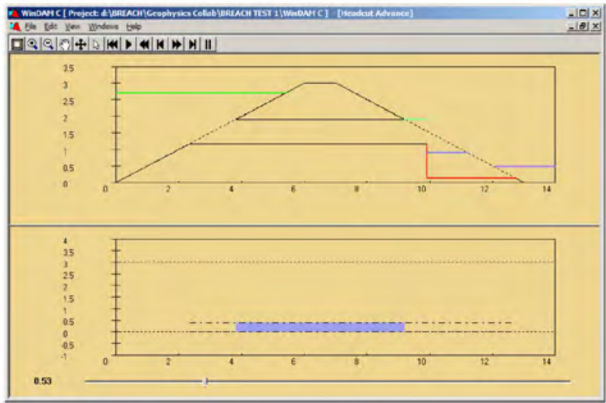


Figure 6. — Incremental erosion during internal erosion test of homogeneous silty clay embankment.

Total elapsed time = 48 minutes

Post-test modeling: WinDAM C

- WinDAM C is a dam breach model developed by USDA to simulate overtopping and internal erosion failures of homogeneous cohesive embankments



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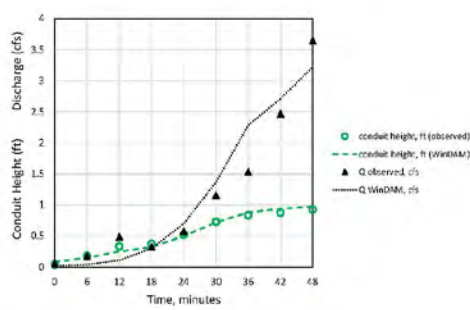
Post-test modeling: WinDAM C

- Good match of predicted breach outflows and internal erosion conduit sizes when we used k_d=2 ft/hr/psf and initial conduit size of 1 inch
- Close to actual conditions:
  - 0.5-inch rebar could have disturbed a larger area
  - k_d = 5.5 ft/hr/psf measured with JET



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Zoned Embankment Objectives

- Not much experience with failure of rockfill dams
- Rockfill dams are difficult to evaluate
  - What are erodibility parameters (especially k_d) for gravelly soils?
  - How do different zones interact and affect one another?
- There are rockfill dams upstream from several U.S. nuclear facilities

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What is rockfill?

- Consultations with embankment designers at USBR, USACE, etc.
  - Materials in rockfill dams vary widely
  - Usually broadly graded
  - Often "dirtier" than expected
  - Variability of behavior is common because segregation and layering often occur during construction

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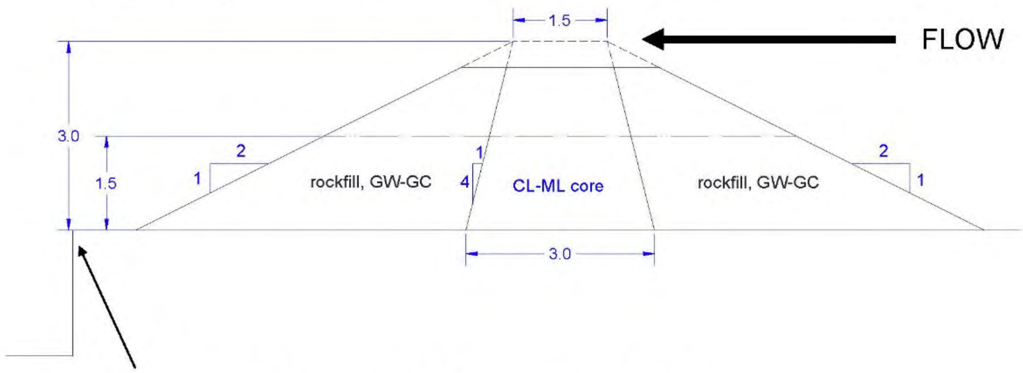
Zoned Embankments

- **Modeled a relatively simple embankment design**
  - **Did not include modern features such as filters,**



Note overfall immediately below embankment

Soils

- **Rockfill zones represented by a Class 6 road base soil from local aggregate supplier**
  - **GW-GC (Well-Graded Gravel with Clay and Sand)**
  - **12% fines (passing #200 sieve) with CL-ML (Silty Clay) classification**

    LL=25, PI=6
- **Core is also CL-ML (Silty Clay)**

  86% fines
  LL=27, PI=6

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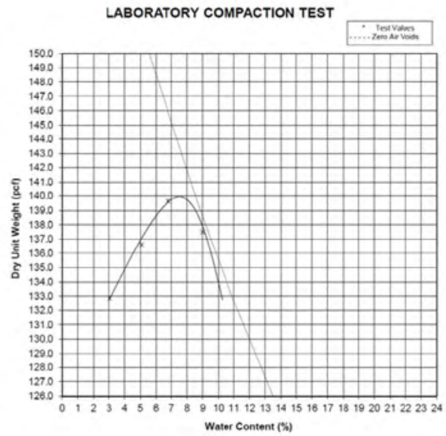
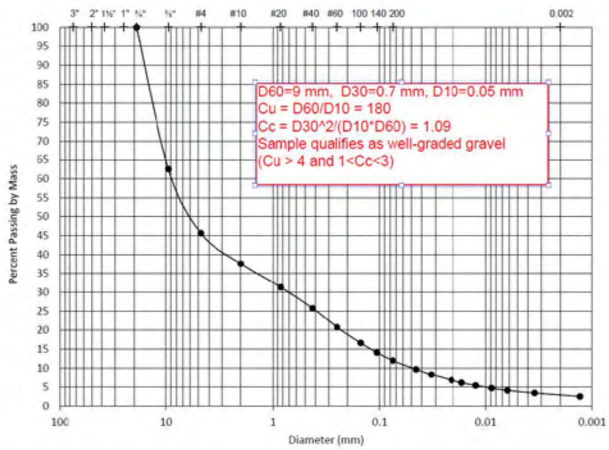
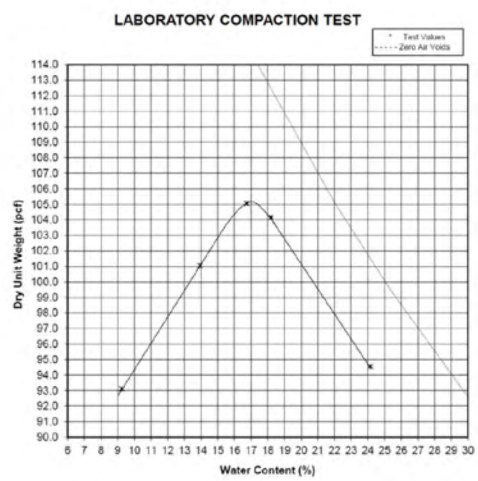
GW-GC Rockfill

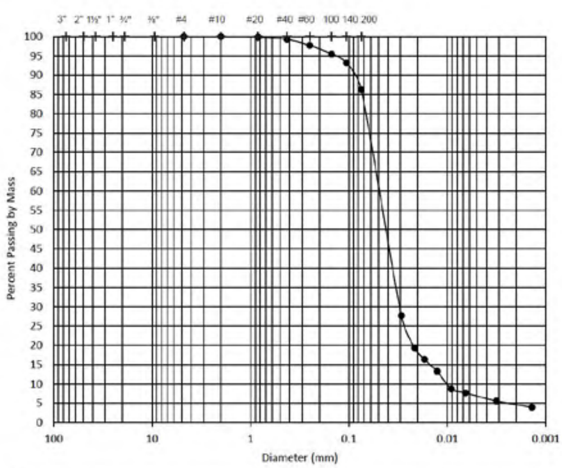




Cobbles (%)	Gravel (%)		Sand (%)			Fines (%)	
	54.3		33.7			12.0	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
		54.3	8.1	11.8	13.8	9.2	2.8

CL-ML Core





Cobbles	Gravel		Sand			Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay

Cobbles (%)	Gravel (%)		Sand (%)			Fines (%)	
			13.7			86.3	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
				0.8	13.0	79.5	6.7

Embankment Construction

JET test of core

Sand cone tests also performed to measure density of core and gravel zones

Approx. 100% of standard Proctor for all zones

Overtopping Test – 3 minutes

Overtopping Test – 5 minutes

Overtopping Test – 7 minutes

Overtopping Test – 14 minutes

Overtopping Test – 19 minutes

Overtopping Test – 26 minutes

Overtopping Test – 33 minutes

Overtopping Test – 37 minutes

Overtopping Test – 47 minutes

Overtopping Test – 77 minutes

Overtopping Test – 120 minutes

Overtopping Test – 180 minutes

End of Test

End of Test

Material Behavior - cohesive

Observations

- Although core and gravel zones both showed cohesive behavior (near-vertical sidewalls), erosion did not adopt a headcut pattern
- Surface erosion was dominant
  - Lack of tailwater pool to provide recirculation and accelerate erosion at toe

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Post-Test Analysis

- Estimate erosion rates and hydraulic stresses from photo records and use to estimate values of k_d

$$\varepsilon_r = k_d (\tau - \tau_c)$$

- Compare to Jet Erosion Tests (JETs) of soil in downstream rockfill zone

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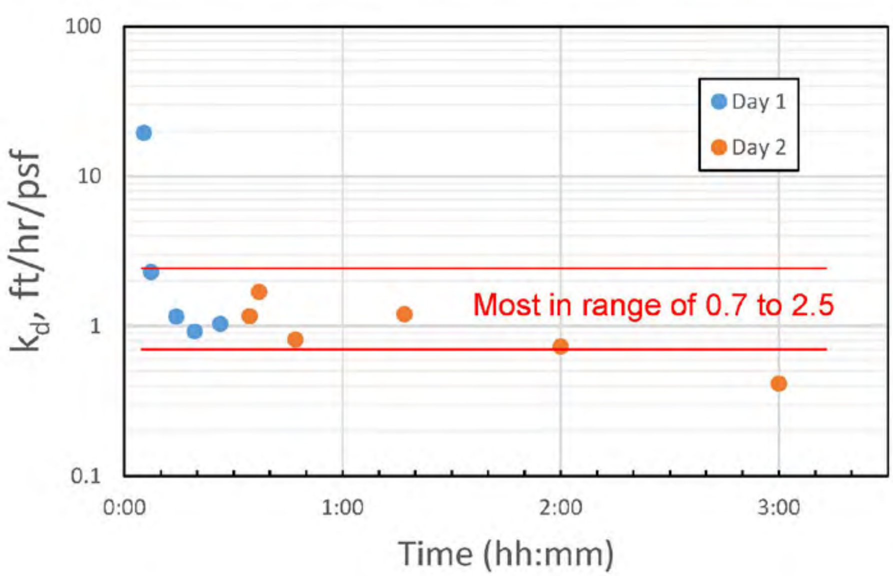
Estimate k_d from photos

Table 1. — Flow and breach channel properties used to estimate value of k_d for gravel zone.

Elapsed time	Channel width	Flow depth	Discharge	Velocity	Channel slope	Manning's n	Shear stress, $\tau_e = \gamma RS(n_s/n)^2$	Bed position normal to slope, ft	k_d
hh:mm:ss	ft	ft	ft^3/s	ft/s	ft/ft	-	lb/ft^2	ft	ft/hr/lb/ft^2
0:03:20	1.10	0.23	0.61	2.42	0.51	0.130	0.158	0.34	---
0:05:20	1.16	0.23	0.73	2.69	0.53	0.122	0.193	0.45	19.59
0:07:20	1.22	0.24	0.84	2.92	0.57	0.118	0.225	0.47	2.31
0:14:20	1.42	0.24	1.17	3.43	0.58	0.105	0.305	0.51	1.16
0:19:20	1.57	0.24	1.50	3.94	0.60	0.095	0.398	0.54	0.93
0:26:20	1.77	0.25	1.81	4.13	0.60	0.093	0.432	0.59	1.04
0:34:28	2.07	0.25	2.01	3.88	0.62	0.104	0.376	0.64	1.17
0:37:00	2.08	0.26	2.01	3.79	0.58	0.103	0.357	0.67	1.70
0:47:00	2.10	0.29	2.21	3.61	0.53	0.112	0.313	0.71	0.82
1:17:00	2.16	0.38	2.5	3.02	0.49	0.148	0.204	0.82	1.21
2:00:00	2.25	0.61	3.63	2.66	0.45	0.201	0.141	0.88	0.73
3:00:00	2.38	0.64	4.55	3.00	0.32	0.157	0.177	0.95	0.41

Estimates of k_d from photos



Jet Erosion Tests

- Hypothesis is that erodibility of mixed soils (granular & cohesive) is primarily determined by the cohesive fraction
  - Presence of gravel may also add marginally to erosion resistance (armoring, shielding)
- Used ASTM D4718 procedure to calculate a gravel correction to determine effective density and water content of the finer fractions of the well-graded gravel
  - Minus No. 4 and minus 3/8” fractions

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JET specimens

- Two minus No. 4’s compacted by hand to achieve calculated target densities (comparable to 100% standard Proctor)
- Two minus No. 4’s using modified Proctor (4.5 times more energy) (109-114%)
- One minus 3/8” at standard Proctor
- One minus 3/8” at modified Proctor
- One whole gravel specimen at standard Proctor

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JET results

Minus No.4, standard compaction specimens were a little more erodible than gravel zone in embankment, but in same order of magnitude

ID	Specimen	Water content, w, %	Dry density, γ_d, lb/ft³	Water content of minus No. 4, w_{-4}, %	Dry density of minus No. 4, γ_{d-4}, lb/ft³	Compaction method	Detachment rate coefficient, k_d, ft/hr/lb/ft²	Critical shear stress, τ_c, lb/ft²
-	Reference	7.0	140.0	12.4	114.3	-	-	-
1	Minus No. 4 fraction	12.4	113.2	12.4	113.2	5-layers, target γ_d = 114 lb/ft³ w = 12.5%	5.1	0.00024
2	Minus No. 4 fraction	12.8	112.9	12.8	112.9	5-layers, target γ_d = 114 lb/ft³ w = 12.5%	4.9	0.00029
3	Minus No. 4 fraction	13.0	124.8	13.0	124.8	modified Proctor, 56,250 ft-lb/ft³	0.63	0.025
4	Minus No. 4 fraction	11.4	130.3	11.4	130.3	modified Proctor	0.45	0.046
5	Minus 3/8-inch	11.0	132.3	14.2	121.7	standard Proctor, 12,375 ft-lb/ft³	1.01	0.0056
6	Minus 3/8-inch	10.3	133.7	13.2	123.3	modified Proctor	0.31	0.044
7	Full sample	8.4	140.3	15.5	114.8	standard Proctor	3.1	0.07

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JET results

- Minus No.4, modified compaction showed increased erosion resistance.
- Lower layers of embankment may have been overcompacted when upper layers were added.

ID	Specimen	Water content, w, %	Dry density, γ_d, lb/ft³	Water content of minus No. 4, w_{-4}, %	Dry density of minus No. 4, γ_{d-4}, lb/ft³	Compaction method	Detachment rate coefficient, k_d, ft/hr/lb/ft²	Critical shear stress, τ_c, lb/ft²
-	Reference	7.0	140.0	12.4	114.3	-	-	-
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6	Minus 3/8-inch	10.3	133.7	13.2	123.3	modified Proctor	0.31	0.044
7	Full sample	8.4	140.3	15.5	114.8	standard Proctor	3.1	0.07

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JET results

- Minus 3/8" specimens both showed more erosion resistance than comparable minus No. 4 specimens.
- Could be due to other factors. More testing needed to confirm trend.

ID	Specimen	Water content, w, %	Dry density, γ_d, lb/ft³	Water content of minus No. 4, w_{-4}, %	Dry density of minus No. 4, $\gamma_{d\text{-}4}$, lb/ft³	Compaction method	Detachment rate coefficient, k_d, ft/hr/lb/ft²	Critical shear stress, τ_c, lb/ft²
-	Reference	7.0	140.0	12.4	114.3	-	-	-
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7	Full sample	8.4	140.3	15.5	114.8	standard Proctor	3.1	0.07

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JET results

Full gravel specimen was more erodible again, but still close to range of estimates for embankment rockfill zone. This specimen is probably pushing the limits for doing a valid JET test (too much gravel, too big).

ID	Specimen	Water content, w, %	Dry density, γ_d, lb/ft³	Water content of minus No. 4, w_{-4}, %	Dry density of minus No. 4, $\gamma_{d\text{-}4}$, lb/ft³	Compaction method	Detachment rate coefficient, k_d, ft/hr/lb/ft²	Critical shear stress, τ_c, lb/ft²
-	Reference	7.0	140.0	12.4	114.3	-	-	-
1	Minus No. 4 fraction	12.4	113.2	12.4	113.2	5-layers, target γ_d = 114 lb/ft³ w = 12.5%	5.1	0.00024
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5	Minus 3/8-inch	11.0	132.3	14.2	121.7	standard Proctor, 12,375 ft-lb/ft³	1.01	0.0056
6	Minus 3/8-inch	10.3	133.7	13.2	123.3	modified Proctor	0.31	0.044
7	Full sample	8.4	140.3	15.5	114.8	standard Proctor	3.1	0.07

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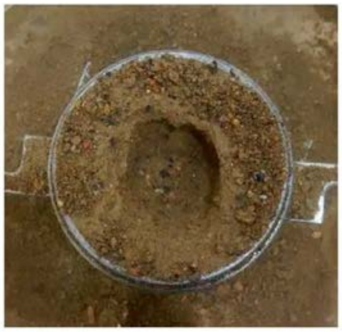
JETs



Minus No. 4 (3/16")　　minus 3/8"　　full gravel up to ¾"

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Piping Test (Internal Erosion)

- **Embankment was reconstructed only in the area affected by first test (near abutment)**

½" rebar
18 inches below crest

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Piping Test

- Took place over four days (48 hours of flow)
  - Day 1
    - Reservoir was filled and rebar withdrawn
    - Initial flow through "pipe" probably less than 5 gpm
    - Initially turbid, but gradually cleared
    - Within 90 minutes, flow stopped completely

    - Pipe healed itself
    - No erosion was ever visible through the acrylic left abutment wall

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Healing of Pipe

- Gravel zone met basic criteria to serve as a filter for the core

$$\frac{D_{15,filter}}{D_{15,base}} \geq 5$$

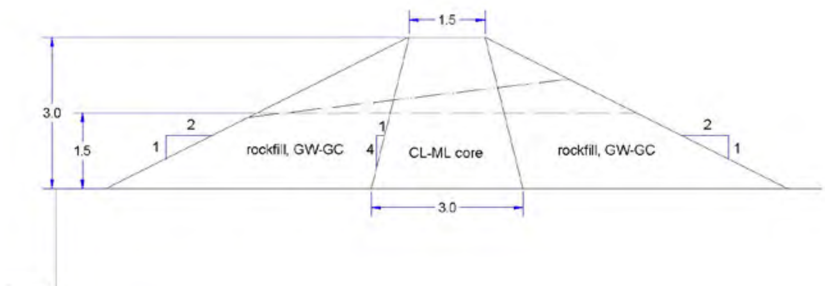
$$\frac{D_{15,filter}}{D_{85,base}} \leq 5$$

$$\frac{0.12\ mm}{0.015\ mm} = 8.0$$

$$\frac{0.12\ mm}{0.07\ mm} = 1.7$$

Day 2

- Interventions to try to initiate a failure and then observe erosion processes
  - Reinserted rebar and withdrew again



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Day 2

- Flow was again initially turbid, then cleared
- Flow rate remained steady (about 5 gpm)
- Hole through downstream gravel zone gradually became more distinct as fines and fine sand were carried away
  - Further growth of hole was limited by medium to coarse sand and fine gravel left behind
  - Enlargement of hole through core zone became visible after 19 minutes

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Internal Erosion – 1 minute

Internal Erosion – 5 minutes

Internal Erosion – 10 minutes

Internal Erosion – 20 minutes

Internal Erosion – 30 minutes

Internal Erosion – 60 minutes

Internal Erosion – 90 minutes

Internal Erosion – 2 hours

Internal Erosion – 3 hours

Internal Erosion – 4 hours

Internal Erosion – 6 hours

Internal Erosion – 9 hours

Internal Erosion – 12 hours

Internal Erosion – 15 hours

Failure Modes

- Erosion process is leading to a slow "stoping" failure
  - Upward migration of erosion channel as roof slowly collapses and void increases in size
  - As stope rises, this could eventually cause a collapse of the crest that could produce…
    - Overtopping
    - Shortened seepage path -- increased hydraulic gradient
- Downstream and upstream gravel zones limiting flow, keeping process slow

64

Internal Erosion – 24 hours

Internal Erosion – 36 hours

Takeaways from Piping Test

- **Numerical models of embankment breach by internal erosion assume a concentrated leak and model only the detachment and removal of soil to enlarge that leak**
  - **Re-deposition of material collapsing from roof is not modeled**
  - **Simulating the "stoping" mechanism is beyond capabilities of current models**
- **Limitation of flow by upstream/downstream gravel zones is also not well represented in numerical models**

Internal Erosion "Toolbox"

- **USBR and US Army Corps of Engineers (USACE)**
  - Best Practices in Dam and Levee Safety Risk Analysis
    - Chapter IV-4, Internal Erosion Risks for Embankments and Foundations, https://www.usbr.gov/ssle/damsafety/risk/methodology.html
- **Set of empirical and experienced-based procedures for analyzing the sequence of events (event-tree) needed for internal erosion failure modes**

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Internal Erosion "Toolbox"

- **USBR and US Army Corps of Engineers (USACE)**
  - Best Practices in Dam and Levee Safety Risk Analysis
    - Chapter IV-4, Internal Erosion Risks for Embankments and Foundations, https://www.usbr.gov/ssle/damsafety/risk/methodology.html
- **Set of empirical and experienced-based procedures for analyzing the sequence of events (event-tree) needed for internal erosion failure modes**

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Typical Internal Erosion Event Tree

Water level at or above threshold level

- Initiation – Erosion starts
  - Continuation – Unfiltered or inadequately filtered exit exists
    - Progression – Continuous stable roof and/or sidewalls
      - Progression – Constriction or upstream zone fails to limit flows
        - Progression – No self-healing by upstream zone
          - Unsuccessful detection and intervention
            - Breach (uncontrolled release of impounded water)

For this embankment, projected breach rate is Rapid to Medium, 1 to 7 days

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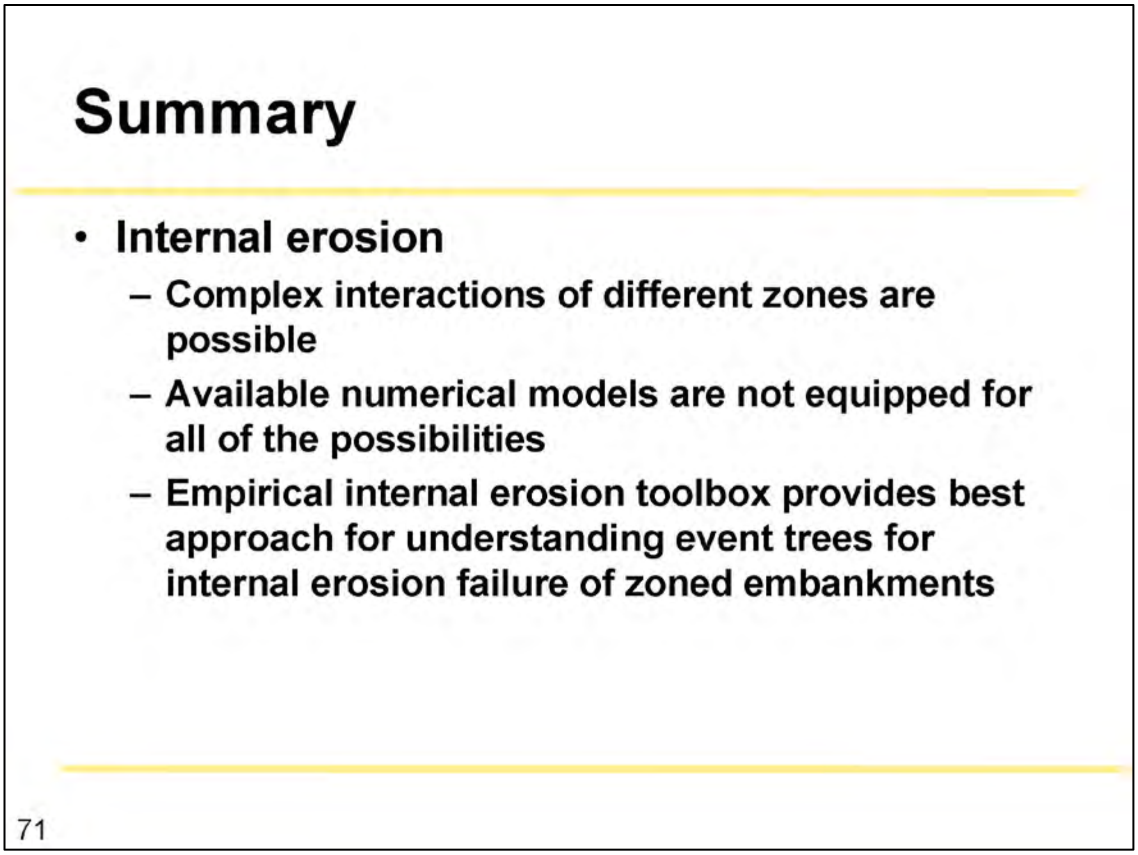
Summary

- Overtopping test
  - Erodibility (k_d) of gravel zone estimated from embankment test observations matches well with JET tests
  - Understanding erodibility of mixed gravel & cohesive soils is a big challenge as ratio of coarse-to-fine soil changes
  - This gravel had enough fines to behave like a cohesive soil, but what about…
    - Cleaner rockfills ???
    - Cobbles and boulders???
  - There is still uncertainty predicting when headcut erosion or surface erosion will take place

70



3.3.8.5.3 Questions and Answers

None.

3.3.9 Day 2: Session 2B - Frameworks I

Session Chair: John Weglian , EPRI

Development and demonstration of a PFHA framework for flood hazard curve estimation.

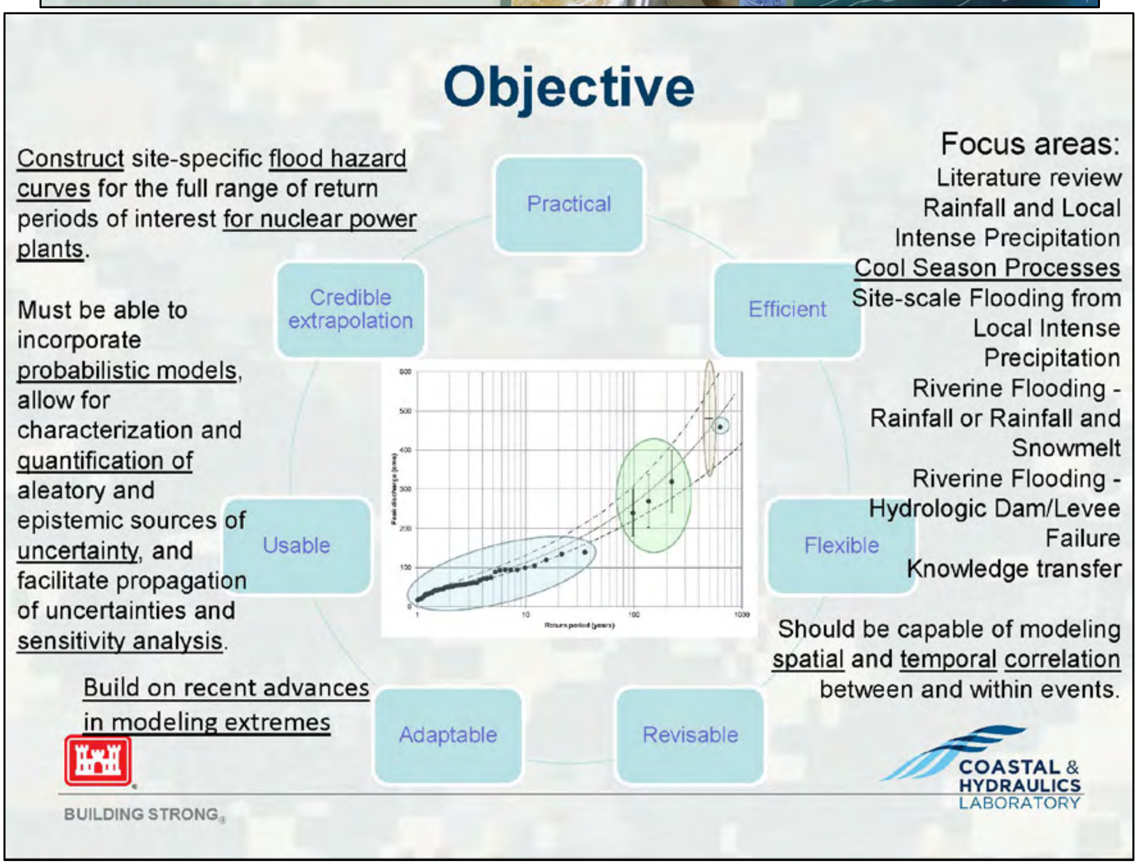
3.3.9.1 A Framework for Inland Probabilistic Flood Hazard Assessments: Analysis of Extreme Snow Water Equivalent in Central New Hampshire

Brian Skahill*, Ph.D. and Carrie Vuyovich, Ph.D., U.S. Army Corps of Engineers, Engineer Research and Development Center (Session 2B-1; ADAMS Accession No. ML17355A074)

3.3.9.1.1 Abstract

The NRC Probabilistic Flood Hazard Assessment (PFHA) research plan aims to build upon recent advances in deterministic, probabilistic, and statistical modeling of extreme events to develop regulatory tools and guidance for NRC staff with regard to PFHA for nuclear facilities. For inland nuclear facility sites (i.e., non-coastal sites), a PFHA must be able to incorporate probabilistic models for a variety of processes, allow for characterization and quantification of aleatory and epistemic sources of uncertainty, and facilitate propagation of uncertainties and sensitivity analysis. Moreover, the PFHA framework should be capable of modeling spatial and temporal correlation between and within events. The bases for the framework are two distinct spatial analysis methodologies for characterizing hazard curves that each in their own right are recent advances in the modeling of extreme events. The two spatial methods were selected as the basis given that most relevant flood hazard phenomena naturally occur as spatial processes and regionalization is likely a minimum requirement toward improved accuracy and precision of estimates. Related, the two methods are each designed in a manner such that they, or their respective adaptions, can be readily applied to leverage any and all available relevant information for a given hazard analysis. The first method is spatial or spatiotemporal Bayesian Hierarchical Modeling (BHM); whereas, the second approach employs max-stable processes. The application of either approach involves the use of spatial and temporal covariate data to distribute model parameters in space and also account for temporal trends. The spatial/spatiotemporal BHM methodology is simple and flexible and leverages the multiple merits of Bayesian inference to support probabilistic flood hazard analyses to readily develop spatially coherent pointwise return level maps. However, its likelihood formulation assumes conditional independence among the extremes, which can be difficult to ignore for flood hazard phenomenon, and its use of a Gaussian process for the latent variable model results in a lack of conformance with extreme value theory (EVT) . The second framework approach; viz., max-stable processes, when applied does account for the dependence among the extremes, conforms with EVT which is highly notable as framework applications require credible extrapolation well beyond the observed record, and moreover, supports the capacity for more complex areal assessments of risk beyond the simple generation of pointwise return levels. For extreme rainfall and SWE analyses; for example, it is particularly noteworthy that max-stable process applications can develop areal based exceedance probabilities. PFHA framework method choice is dependent upon an initial assessment of dependence among the extreme data. The framework also involves a multi-model averaging step in attempts to account for the uncertainty associated with model choice. We profile a complete application of the framework for the analysis of extreme snow water equivalent data in central New Hampshire which leverages regionalization, additional data derived from process-based hydrologic simulation, climate index data, max-stable process selection, and trend surface modeling analysis to develop individual model and multi-model averaged pointwise return level maps and areal-based exceedance probability estimates.

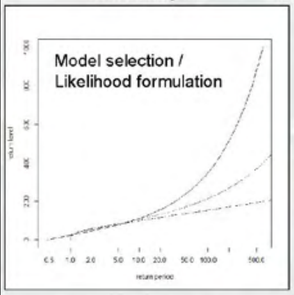
3.3.9.1.2 Presentation



PFHA Framework

Step 1 (Repeat K times)

Data Analysis



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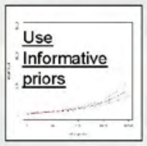
Causal Information Expansion



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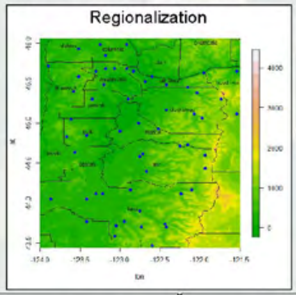
Spatial Information Expansion Data



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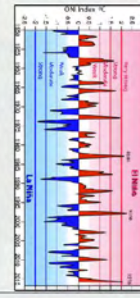
Temporal Information Expansion Data[1]



Climate Index

Historical / Paleoflood Data

Available tools: R packages SpatialExtremes

Spatio-temporal BHM / Spatial Extremes

Step 2 Apply a multi-model averaging technique

For example

Bayesian Model Averaging

$$p(\Delta \mid M_1, \dots, M_k) = \sum_{k=1}^{K} w_k g_k(\Delta \mid M_k)$$

or

Information Criterion Averaging

$$\beta_k = \frac{\exp\left(-\frac{1}{2} I_k\right)}{\sum_{k=1}^{K} \exp\left(-\frac{1}{2} I_k\right)}$$

Available tools: R packages MSClaio2008, SpatialExtremes

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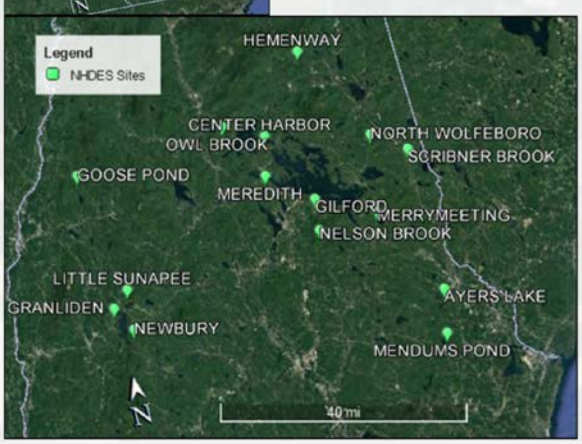
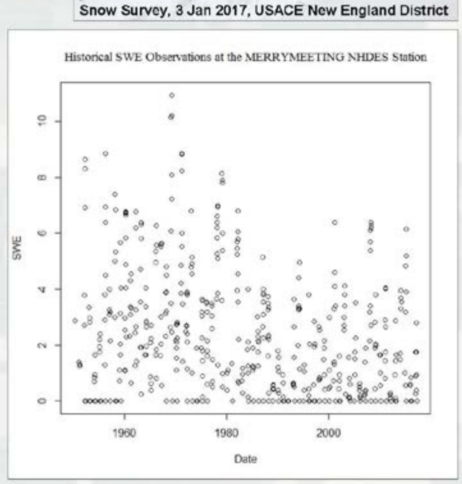
[1]Trenberth, Kevin & National Center for Atmospheric Research Staff (Eds). Last modified 02 Feb 2016. **"The Climate Data Guide: Nino SST Indices (Nino 1+2, 3, 3.4, 4; ONI and TNI)."** Retrieved from https://climatedataguide.ucar.edu/climate-data/nino-sst-indices-nino-12-3-34-4-oni-and-tni.

Demonstration Site & Data

New Hampshire Department of Environmental Services (NHDES) – The NHDES conducts bi-weekly snow surveys throughout the winter season in several basins in central New Hampshire where the agency manages reservoir water supply and releases.

Snow Survey, 3 Jan 2017, USACE New England District





Historical data is available for the period of record on their website:
http://www4.des.state.nh.us/rti_home/snow_sampling_stations.asp

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Causal Information Expansion Data

Livneh daily CONUS near-surface gridded meteorological and derived hydrometeorological data.

The VIC model is a large-scale, semi-distributed hydrologic model

Brief Description:

- This CONUS daily dataset from 1915 to 2011 is 1/16 resolution. The dataset variables have been generated using the Variable Infiltration Capacity **VIC** hydrologic model v.4.1.2.c which was driven with the companion meteorological data.

http://vic.readthedocs.io/en/master/

Temporal Coverage:

- Daily means from 1915/01 to 2011/12
- Monthly means from 1915/01 to 2011/12
- Daily long term means using 1981/01 to 2010/12
- Monthly long term means using 1981/01 to 2010/12

Spatial Coverage:

- .0625 degree latitude x .0625 degree longitude CONUS grid
- 21.21875-52.90625, 235.4688E-293.0312E

Levels:

- Surface

Update Schedule:

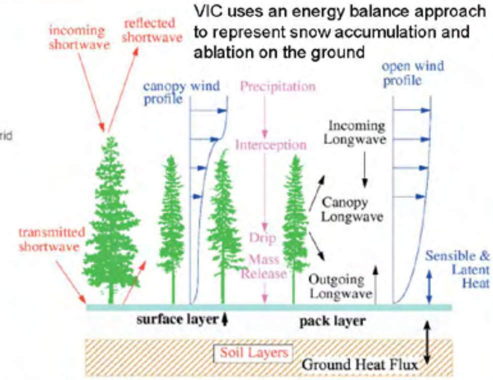
- None

Variables:

- Meteorological Variables(station variables input)
- Flux Variables(model generated)

VIC Snow Algorithm

VIC uses an energy balance approach to represent snow accumulation and ablation on the ground



The land surface is modeled as a grid of large (>>1km), flat, uniform cells

Sub-grid heterogeneity (e.g. elevation, land cover) is handled via statistical distributions

Inputs are time series of sub-daily meteorological drivers (e.g. precipitation, air temperature, wind speed, radiation, etc.)

Land-atmosphere fluxes, and the water and energy balances at the land surface, are simulated at a daily or sub-daily time step

Water can only enter a grid cell via the atmosphere

Livneh data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.esrl.noaa.gov/psd/

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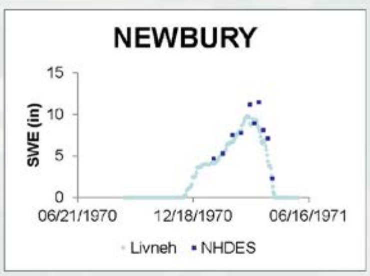
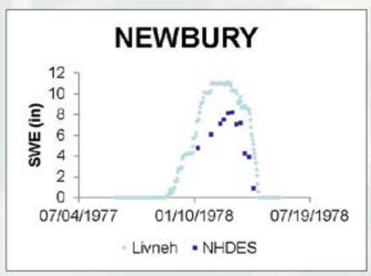
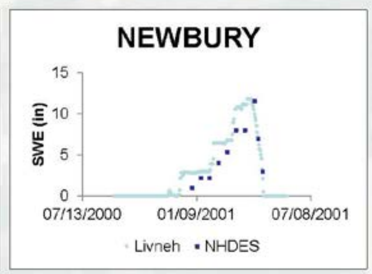
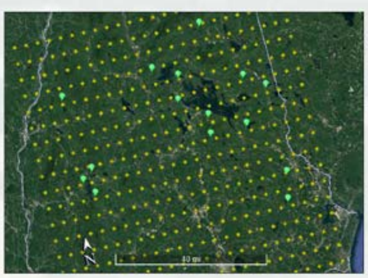
Livneh B., E.A. Rosenberg, C. Lin, B. Nijssen, V. Mishra, K.M. Andreadis, E.P. Maurer, and D.P. Lettenmaier, 2013: A Long-Term Hydrologically Based Dataset of Land Surface Fluxes and States for the Conterminous United States: Update and Extensions, Journal of Climate, 26, 9384–9392.

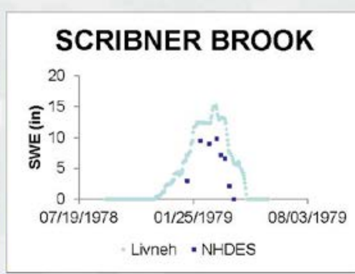
Causal Information Expansion Data

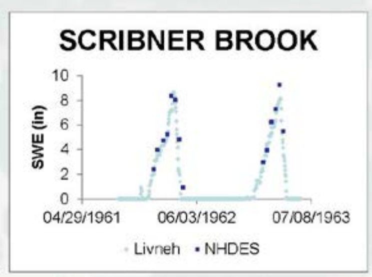












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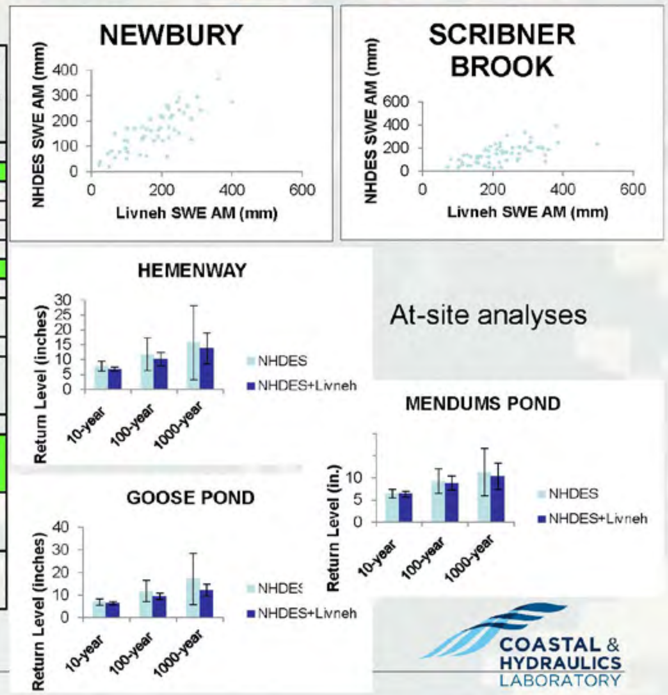
Causal Information Expansion Data

NHDES Site	Observed NHDES data record	Observed NHDES data record length	Remaining record using adjusted Livneh SWE data	Adjusted Livneh SWE data record length
GILFORD	1950 - 2017	68	1915 - 1949	35
GOOSE POND	1972 - 2017	46	1915 - 1971	57
MEREDITH	1950 - 2017	68	1915 - 1949	35
CENTER HARBOR	1950 - 2017	68	1915 - 1949	35
MERRYMEETING	1950 - 2017	68	1915 - 1949	35
OWL BROOK	1951 - 2017	67	1915 - 1950	36
HEMENWAY	1994 - 2017	24	1915 - 1993	79
LITTLE SUNAPEE	1960 - 2017	58	1915 - 1959	45
NORTH WOLFEBORO	1951 - 2017	67	1915 - 1950	36
GRANLIDEN	1960 - 2017	58	1915 - 1959	45
SCRIBNER BROOK	1950 - 1979 + 1981 - 2017	67	1915 - 1949 + 1980	36
NEWBURY	1960 - 2017	58	1915 - 1959	45
MENDUMS POND	1961 - 1979 + 1982 - 2017	55	1915 – 1960 + 1980 - 1981	48
AYERS LAKE	1961 - 1979 + 1982 - 2017	55	1915 – 1960 + 1980 - 1981	48
NELSON BROOK	1961 - 1979 + 1982 - 2017	55	1915 – 1960 + 1980 - 1981	48
	Σ:	882	Σ:	663



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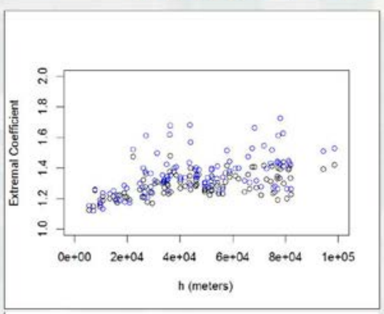
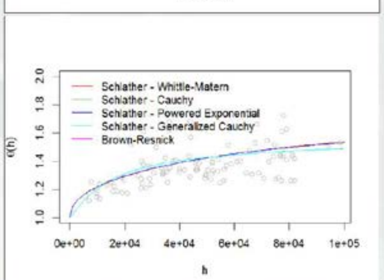
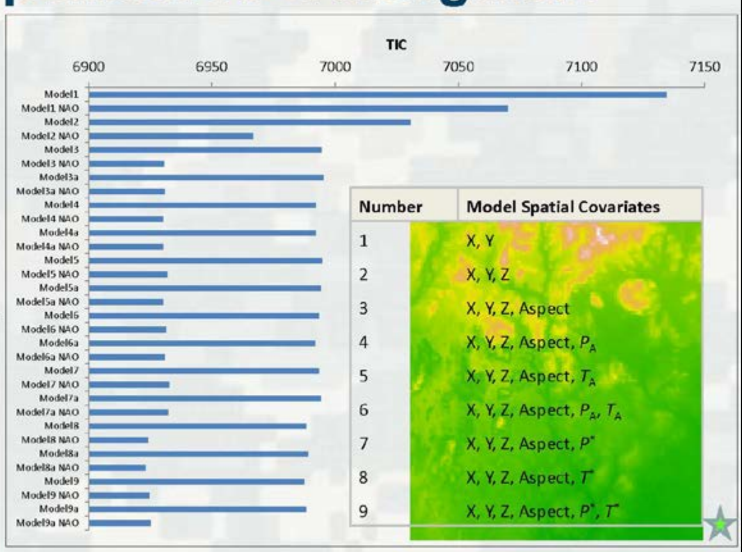
Model Dependence & Marginals







Number	Model Spatial Covariates
1	X, Y
2	X, Y, Z
3	X, Y, Z, Aspect
4	X, Y, Z, Aspect, P_A
5	X, Y, Z, Aspect, T_A
6	X, Y, Z, Aspect, P_A, T_A
7	X, Y, Z, Aspect, P^*
8	X, Y, Z, Aspect, T^*
9	X, Y, Z, Aspect, P^*, T^*

P_A= mean annual precipitation; T_A= mean annual temperature; P^*= mean winter precipitation; T^*= mean winter temperature; a = parsimonized version of model; NAO = use of North Atlantic Oscillation climate Index temporal covariate data

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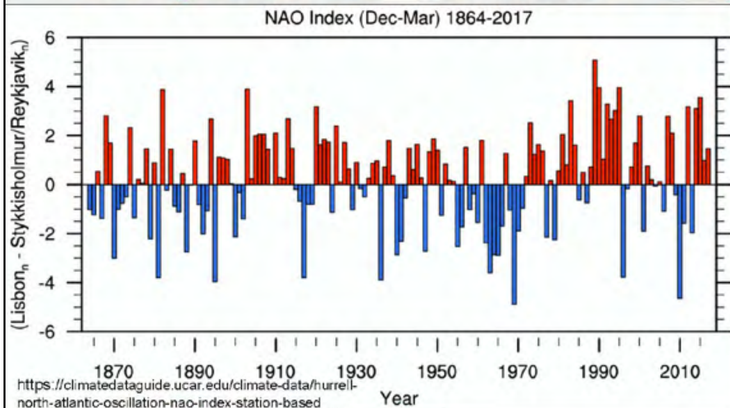
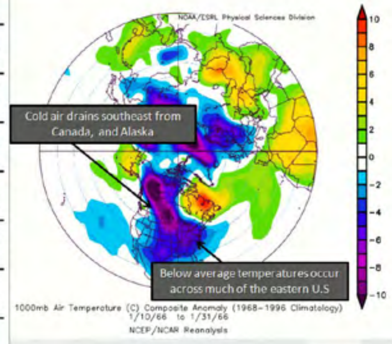
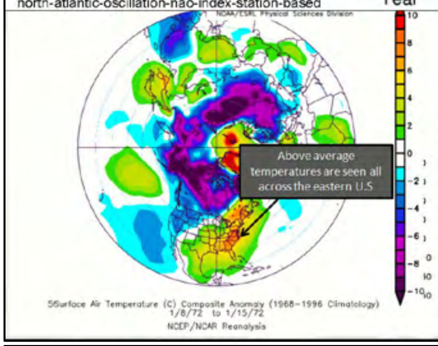
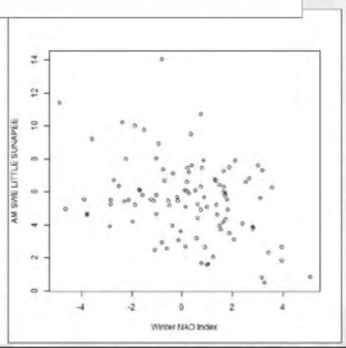
★ = gridded covariate dataset of mean annual temperature

Temporal Information Expansion Data



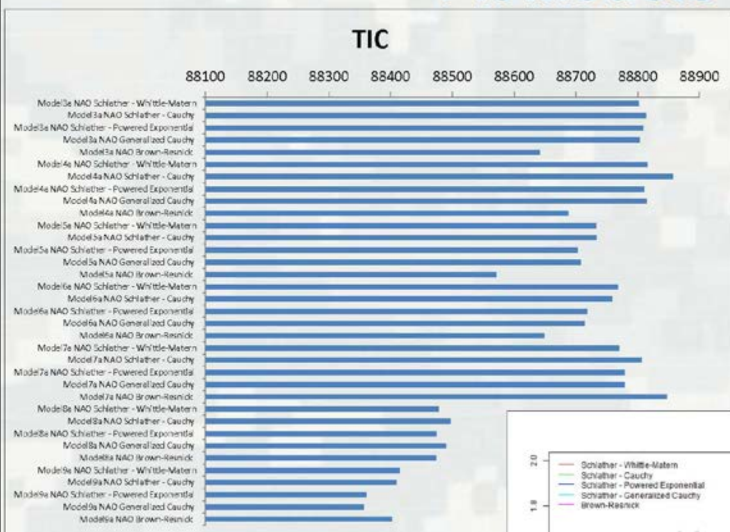


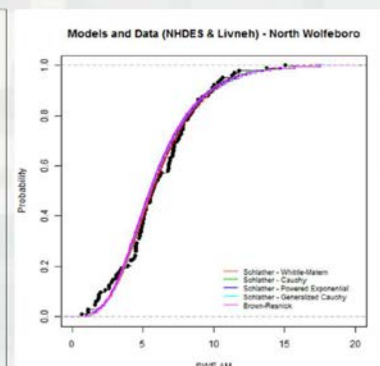




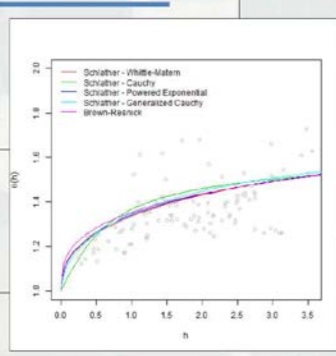
Roughly speaking, the NAO is an atmospheric process with two different phases, positive and negative, which relate to how the atmospheric mass is distributed. The gradient between two large scale pressure cells over the Atlantic Ocean, a low located near Iceland and a high over the Azores, affects the strength of westerlies and storm track direction.

Fit Models





Number	Model Spatial Covariates
3	X, Y, Z, Aspect
4	X, Y, Z, Aspect, P_A
5	X, Y, Z, Aspect, T_A
6	X, Y, Z, Aspect, P_A, T_A
7	X, Y, Z, Aspect, P^*
8	X, Y, Z, Aspect, T^*
9	X, Y, Z, Aspect, P^*, T^*



35 models considered; viz., 3a – 9a, all including use of NAO, and 5 max-stable model configurations

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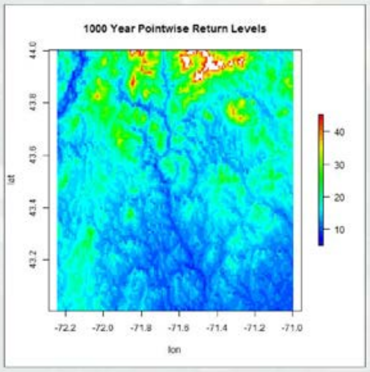
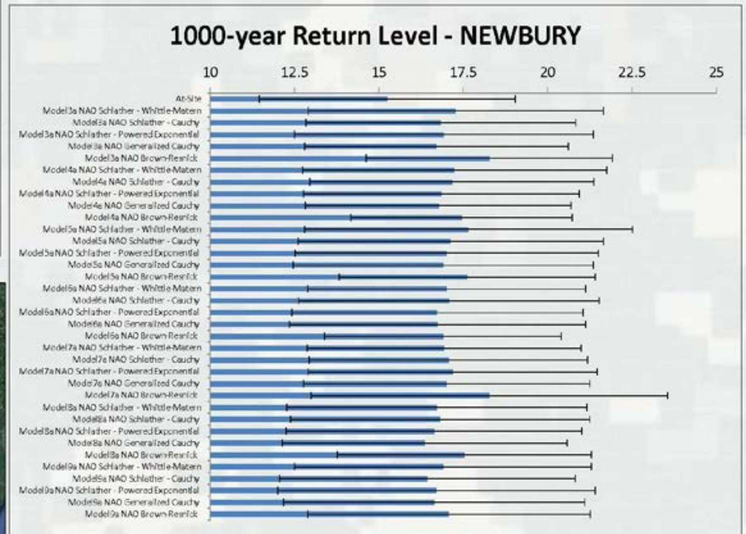


Pointwise Return Levels



Estimate including lower and upper 95% uncertainty bounds

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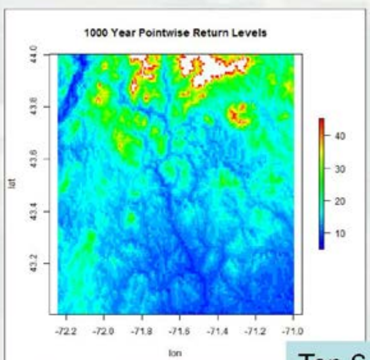
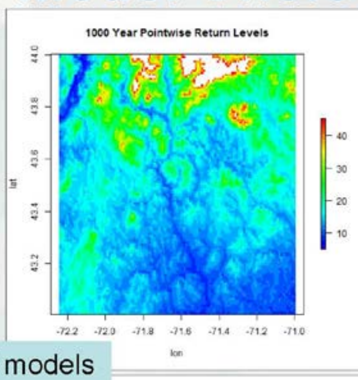
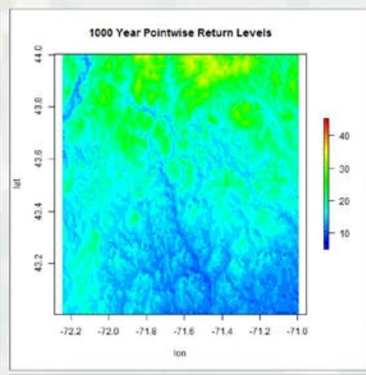
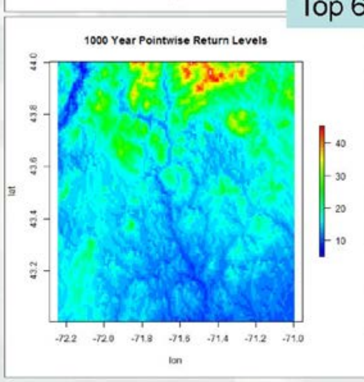
Model Choice

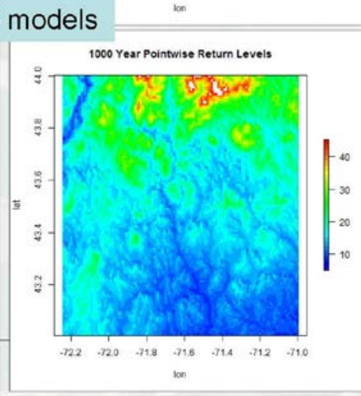


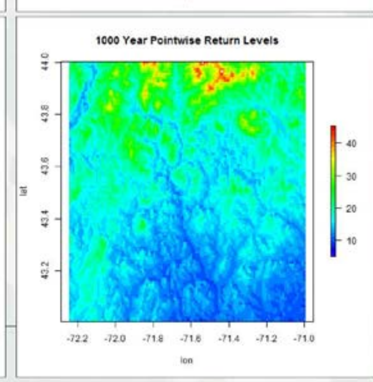




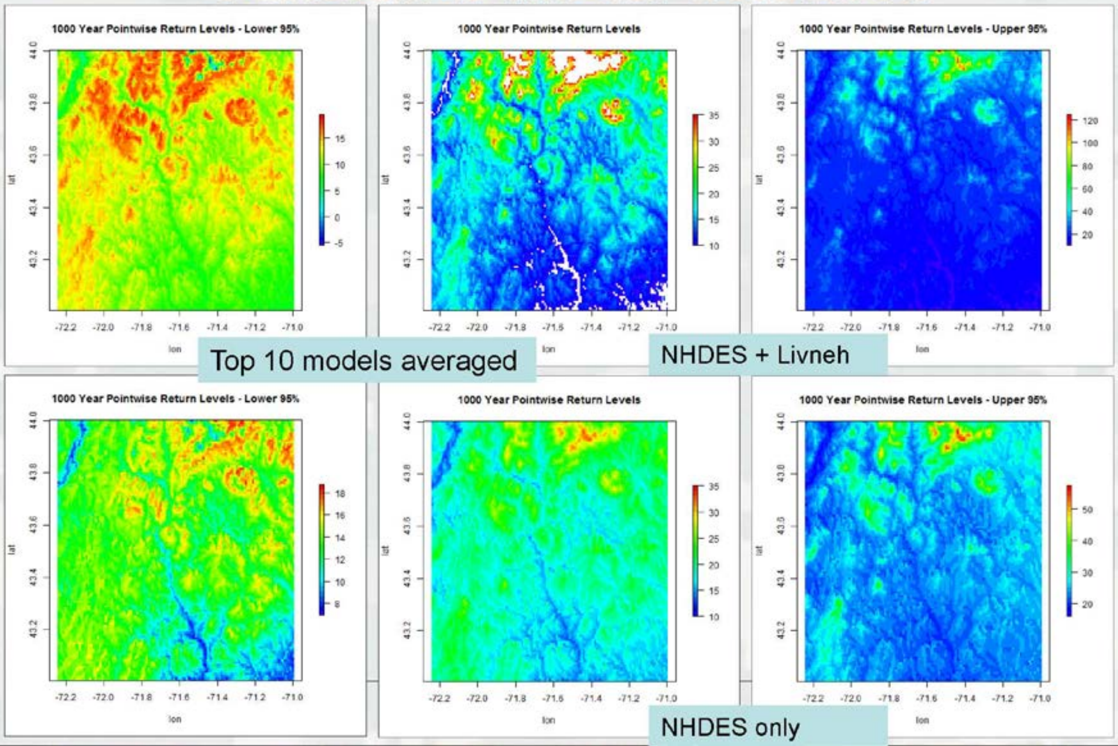
Top 6 models







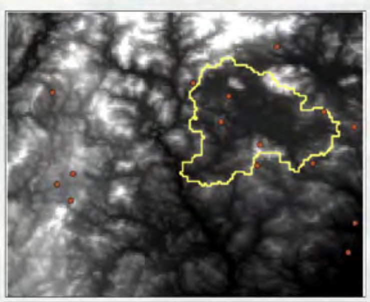
Generalize Model Selection

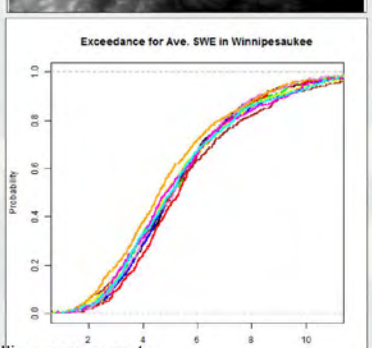


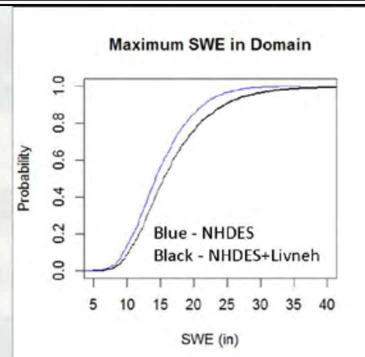
Areal-based Exceedances

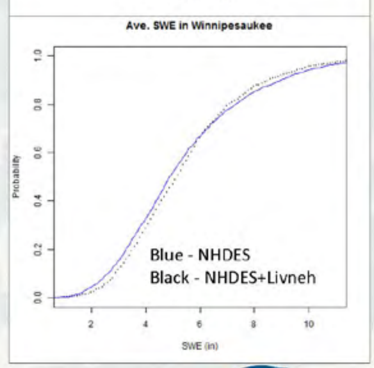
With max-stable process applications, additional more complex assessments of risk can also be evaluated. For example, the joint spatial modeling of observations (e.g., precipitation, snow water equivalent (SWE), snowmelt rate, or temperature), denoted for generality by $\Upsilon(x)$, over a basin $\mathcal{B}$, supports the capacity to compute, via simulation, an integral such as

$$\Pr\left\{\int_{\mathcal{B}} \Upsilon(x)dx > z_{crit}\right\}$$









"By spatially modelling rare events one can simulate unusual episodes rather than merely produce pointwise maps of high quantiles, and thus allowing a more powerful risk analysis."

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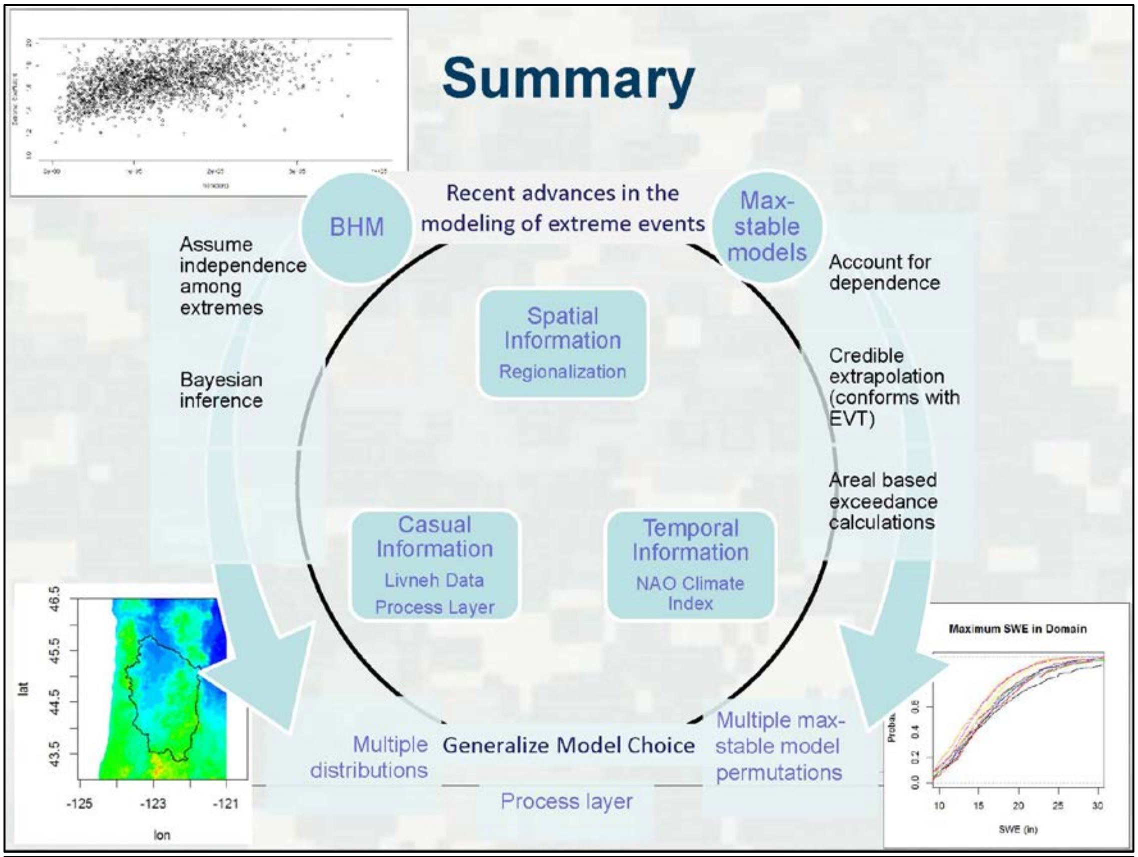
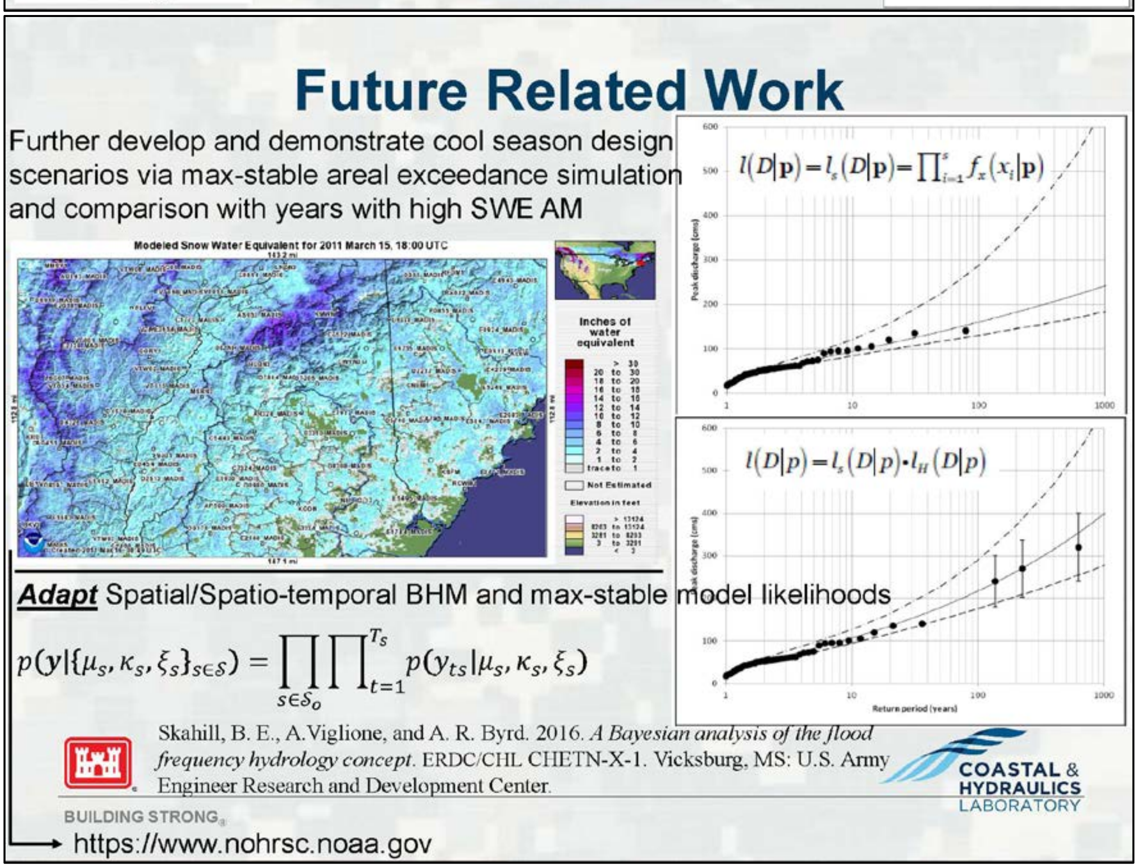
A. C. Davison, M. M. Gholamrezaee, 2012. Geostatistics of extremes. Proceedings of the Royal Society A: Mathematical, Physical and Engineering Science. DOI: 10.1098/rspa.2011.0412.


Summary
Recent advances in the modeling of extreme events
BHM
Max-stable models
Assume independence among extremes
Bayesian inference
Account for dependence
Credible extrapolation (conforms with EVT)
Areal based exceedance calculations
Spatial Information
Regionalization
Casual Information
Livneh Data
Process Layer
Temporal Information
NAO Climate Index
Multiple distributions
Generalize Model Choice
Multiple max-stable model permutations
Process layer
lat
lon
Maximum SWE in Domain
SWE (in)


Future Related Work
Further develop and demonstrate cool season design scenarios via max-stable areal exceedance simulation and comparison with years with high SWE AM
Modeled Snow Water Equivalent for 2011 March 15, 18:00 UTC
Inches of water equivalent
Not Estimated
Elevation in feet
$l(D|\mathbf{p}) = l_s(D|\mathbf{p}) = \prod_{i=1}^{s} f_x(x_i|\mathbf{p})$
$l(D|p) = l_s(D|p) \cdot l_H(D|p)$
Peak discharge (cms)
Return period (years)
Adapt Spatial/Spatio-temporal BHM and max-stable model likelihoods
$p(y|\{\mu_s, \kappa_s, \xi_s\}_{s\in S}) = \prod_{s\in S_o} \prod_{t=1}^{T_s} p(y_{ts}|\mu_s, \kappa_s, \xi_s)$
Skahill, B. E., A. Viglione, and A. R. Byrd. 2016. *A Bayesian analysis of the flood frequency hydrology concept*. ERDC/CHL CHETN-X-1. Vicksburg, MS: U.S. Army Engineer Research and Development Center.
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COASTAL & HYDRAULICS LABORATORY
https://www.nohrsc.noaa.gov

3.3.9.1.3 Questions and Answers

None.

3.3.9.2 Structured Hazard Assessment Committee Process for Flooding (SHAC-F) for Riverine Flooding Rajiv Prasad*, Ph.D.; Pacific Northwest National Laboratory; Kevin Coppersmith*, Ph.D.; Coppersmith Consulting(Session 2B-2; ADAMS Accession No. ML17355A075)

3.3.9.2.1 Abstract

This research project is part of the U.S. NRC's Probabilistic Flood Hazard Assessment (PFHA) Research plan in support of development of a risk-informed analytical approach for flood hazards. The approach is expected to support reviews of license applications, license amendment requests, and reactor oversight activities. Pacific Northwest National Laboratory is leading the development of a structured hazard assessment committee process for flooding (SHAC-F). In previous years, we described the virtual study following a Senior Seismic Hazard Analysis Committee (SSHAC Level 3 process for local intense precipitation (LIP)-generated flood.

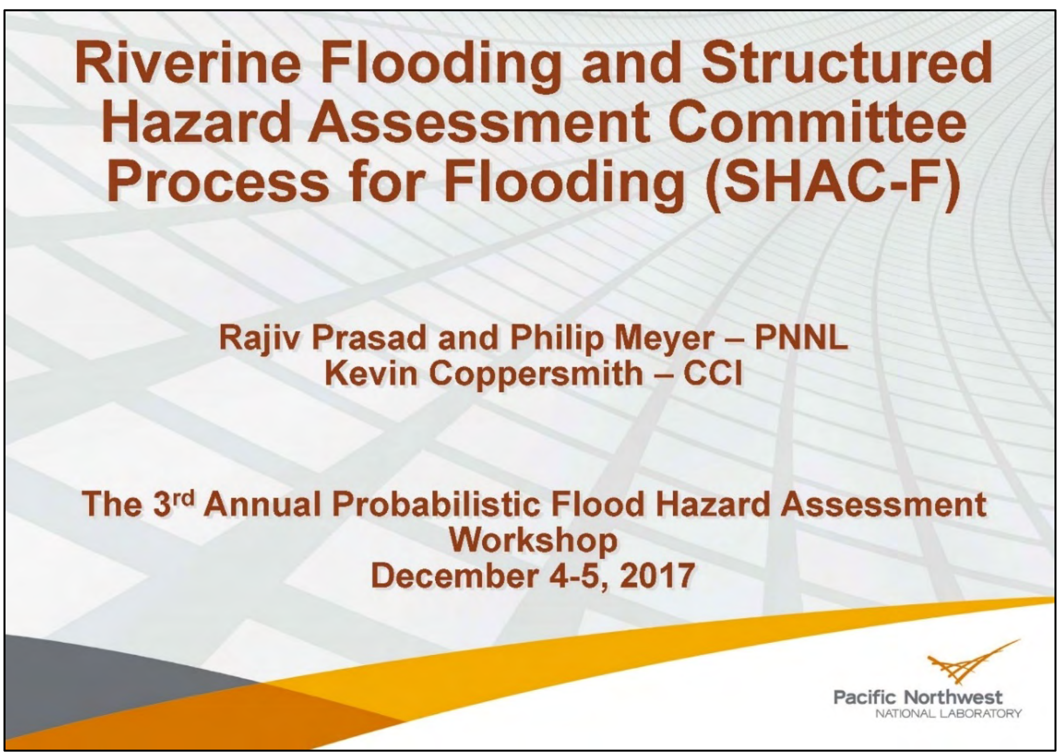
The objective of the current effort is to develop the SHAC- process for riverine flooding (with and without snowmelt but excluding dam breaches) and to provide confidence that all data sets, models, and interpretations proposed by the larger technical community have been given appropriate consideration and that the inputs to the PFHA reflect the center, body, and range of technically defensible interpretations. Several of the issues identified and solutions proposed

during the LIP PFHA SHAC-F virtual study informed the development of riverine SHAC-F process. These issues included precise definition of data and models, compilation of data related to riverine flood characterization, compilation of previous hydrologic and hydraulic models applied to the river basin, and previous characterization of uncertainties in the river basin.

SHAC-F studies can be carried out at three levels which are defined in terms of the purpose of the assessment. Level 1 and Level 2 SHAC-F studies are expected to support NRC's significance determination process. The purpose of a Level 1 study is primarily screening (e.g., binning of flood hazards into high or low risk categories). Level 2 studies would be appropriate to (1) perform a more refined screening analysis (e.g., where a Level 1 study could not adequately support binning of flood hazards) and (2) update an existing Level 3 assessment. The purpose of a Level 3 assessment is to support design reviews and to support probabilistic risk assessment (PRA) for new and existing power reactors. For all three SHAC-F levels, the expected outcome of the study is generation of a family of flood hazard curves appropriate for the purpose of the assessment.

Data and methods used for the three SHAC-F levels are also defined to be commensurate with the purpose of the study. A Level 1 SHAC-F study would use existing data, possibly within an at-site flood-frequency study. The study may use alternative conceptual models (ACMs, various parametric or non-parametric distributions in the case of flood-frequency studies) to represent epistemic uncertainty coupled with regionalization and accounting for nonstationarities. A SHAC-F Level 2 study could supplement flood-frequency analyses with existing simulation model studies. ACMs would include alternative simulation models that can reasonably represent the flood behavior at the site. A SHAC-F Level 3 study would need to account for spatiotemporal resolution of flood hazard predictions that can support licensing and PRA needs. Existing data can be used in a Level 3 study, but a site-specific, detailed analysis would be needed. At all levels of SHAC-F studies, explicit characterization of uncertainty is needed.

3.3.9.2.2 Presentation



SHAC-F Project: Purpose and Approach

- Purpose
  - Adapt the well-established Senior Seismic Hazard Assessment Committee (SSHAC) approach to Probabilistic Flood Hazard Assessment (PFHA)
  - Refer to as the "Structured Hazard Assessment Committee Process for Flooding" (SHAC-F)
  - Develop SHAC-F framework and guidance
- SSHAC process
  - Provides assurance that all data, models, and methods have been evaluated and that full range of knowledge and uncertainties is captured in the hazard analysis
- Approach for development of the SHAC-F framework
  - Based on virtual implementation of the SSHAC process to PFHA for selected flood mechanisms
  - Development of a Template Project Plan for selected flood mechanisms

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SHAC-F Project: Purpose and Approach

- Selected flood mechanisms
  - Local intense precipitation (LIP) flooding
  - Riverine flooding (RF) without snowmelt
  - Riverine flooding from combined rainfall and snowmelt

  RF Virtual Study
- Project adapts and tailors elements of SSHAC process
  - Implementing typical steps of SSHAC to PFHA in virtual studies
  - Documenting lessons learned
  - Refining Template Project Plan
- Activities and Products
  - SHAC-F Work Plan: defines the activities associated with the virtual studies for the SHAC-F project
  - PFHA Template Project Plan: defines all elements of an actual SHAC-F study for a selected flood mechanism
    - Goal is to produce PFHA Template Project Plans
    - Guidance for SHAC-F PFHA studies

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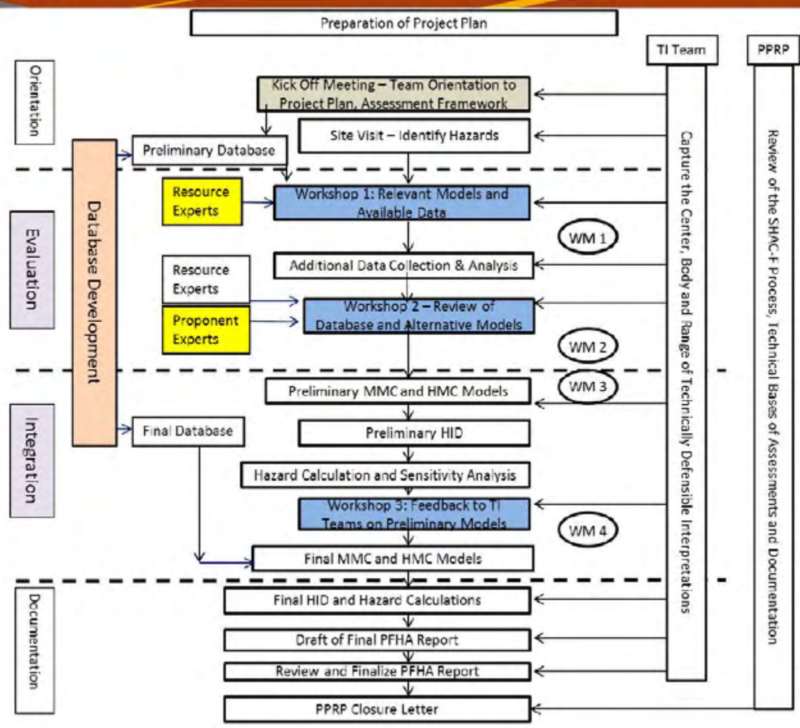
SHAC-F LIP PFHA Project Structure - Workflow



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Lessons Learned from the LIP SHAC-F Virtual Study and Path Forward for Riverine PFHA

- Logistics issues
  - Structured workflow for a Level 3 project; large number of participants
  - Highly site-specific nature of flooding processes
  - Both of these issues raise costs of a SHAC-F study
- September 2017 Project Meeting at Richland
  - SHAC-F Levels are now defined in terms of the purpose of the assessment
    - SHAC-F Levels 1 and 2: support NRC's Significance Determination Process (SDPs)
    - SHAC-F Level 1 to support screening
    - SHAC-F Level 2 to support a more refined screening assessment
    - SHAC-F Level 2 to support update of an existing SHAC-F Level 3 assessment
    - SHAC-F Level 3 to support design reviews and PRAs for new and existing power reactors

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SSHAC Guidelines and Guidance

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Goal of a SSHAC Process

- The fundamental goal of a SSHAC process is to properly carry out and completely document the activities of evaluation and integration, defined as:
  - Evaluation: The consideration of the complete set of data, models, and methods proposed by the larger technical community that are relevant to the hazard analysis.
  - Integration: Representing the center, body, and range of technically defensible interpretations in light of the evaluation process (i.e., informed by the assessment of existing data, models, and methods)."

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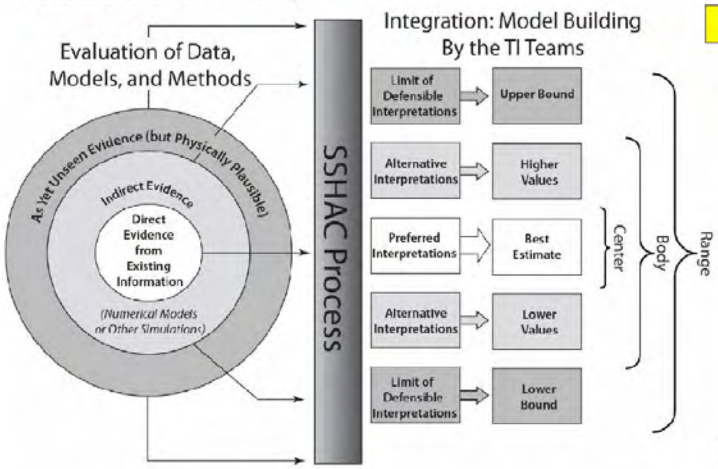

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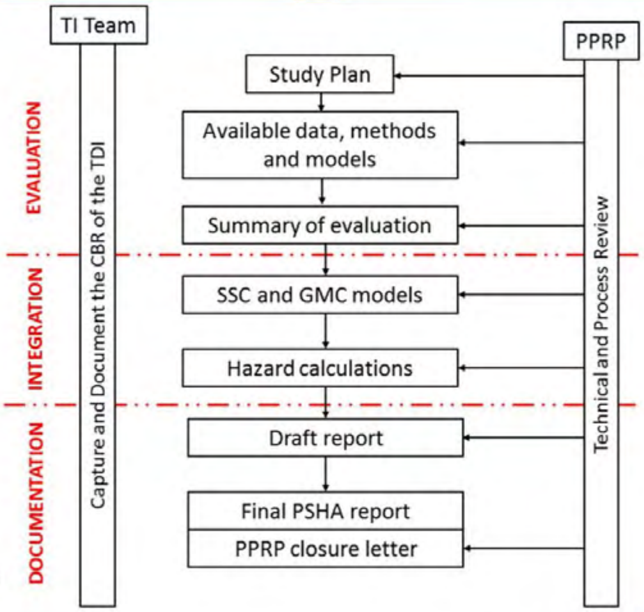
SSHAC Level 1 Project Workflow



PPRP: Participatory Peer Review Panel
TI Team: Technical Integration Team
SSC: Seismic source characterization
GMC: Ground motion characterization team
PSHA: Probabilistic seismic hazard analysis
CBR of the TDI: Center, body, and range of technically defensible interpretations

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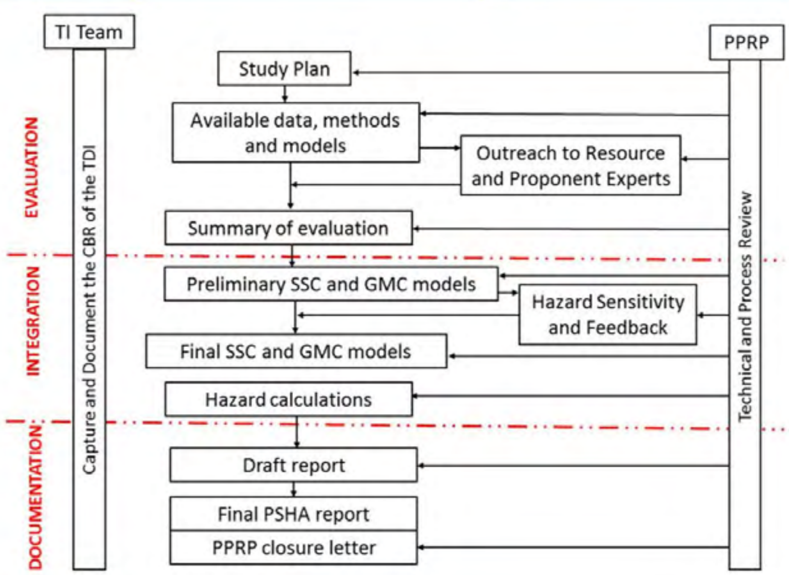
SSHAC Level 2 Project Workflow



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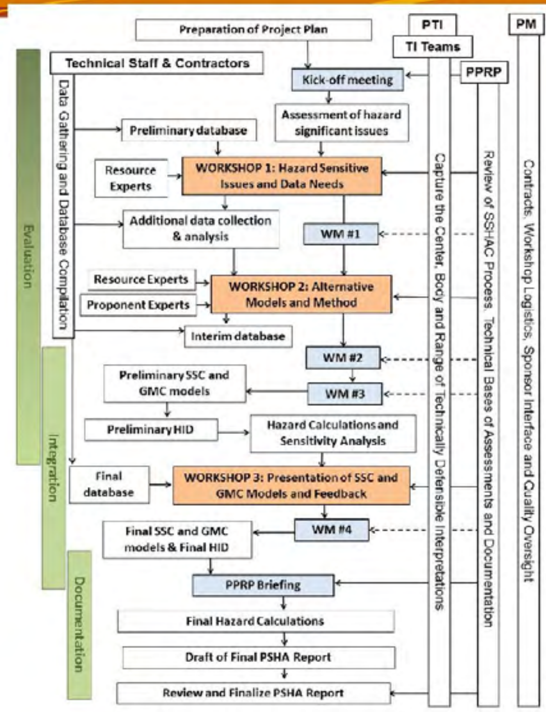
SSHAC Level 3 Project Workflow



NUREG-2213

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SHAC-F Levels – Redefined with Purpose of Assessment (After NUREG-2213 Table 3-1)

Riverine Floods	SHAC-F Level 1	SHAC-F Level 2	SHAC-F Level 3
Purpose	Screening (e.g., binning flood hazards in high or low risk categories)	Update existing Level 3 or refined analysis for screening	Support design PRA for licensing new and built plants
	Significance Determination		
Expected Outcome	Family of Discharge/Elevation Hazard Curves relevant to the system you are analyzing (need to revisit)	Family of Hazard Curves plus associated effects	Family of Hazard Curves plus associated effects
Data	• Stage/Discharge Data • (systematic at site data including historic information) • Regional and Paleo data if available • (flood frequency) • Use what you have	• Discharge Data • Regional Data • Historic and Paleo data • (flood frequency) • Use what you have • More extensive effort to find and assemble existing data • Contact resource experts for simulation model data	• Discharge Data • Regional Data • Historic and Paleo data • (flood frequency) • Use what you have • More extensive effort to find and assemble existing data • Contact resource experts for simulation model data
Models	• Screening flood frequency model • Conceptual Model • ACM – L1 • Statistical Models • Process understanding influencing data • Single population • Regionalization • Nonstationarity	• ACM – L2 • Consider spatial variation • Simulation models	• Conceptual Model • ACM – L3 • Statistical plus simulation • Spatiotemporal resolution of model predictions to support PRA • Locations of SSCs
Principal Sources of aleatory variability	Streamflow	Streamflow (possibly precipitation, basin initial conditions)	Streamflow, precipitation, basin initial conditions,
Principal sources of epistemic uncertainty	Measurement uncertainty in discharge data, alternative statistical models, parameter uncertainty	Measurement uncertainty in discharge data, alternative statistical models, parameter uncertainty in simulation model parameters	Measurement uncertainty in discharge data, alternative statistical models, parameter uncertainty in simulation model parameters

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SHAC-F Levels – Redefined with Purpose of Assessment (After NUREG-2117 Rev. 2 Table 3-1) (cont.)

Riverine Floods	SHAC-F Level 1	SHAC-F Level 2	SHAC-F Level 3
TI Team Makeup	Small TI Team (e.g., two-one in flood frequency modeling, one in regional hydrologic modeling)	Small TI Team; possibly multiple teams (e.g., probabilistic modeler, precipitation frequency analyst, and runoff/hydraulic modeler)	Larger TI Team members (alternative models may require additional TI team members, e.g., probabilistic modeler, precipitation frequency analyst, and runoff/hydraulic modeler)
PPRP	Small PPRP Team (e.g., two-one for flood frequency modeling review and one for regional hydrologic modeling review)	Two or more reviewers (e.g., one/more for flood frequency, one/more for simulation modeling, one/more for regional hydrologic modeling); Feedback on preliminary models; Communication with PPRP during evaluation and integration	Larger team of reviewers (e.g, precipitation and runoff experts, experts in use of potential runoff/hydraulic models, PRA expert); Feedback on preliminary models; Engagement during evaluation and integration process; PPRP briefing of final model
Others from Table 3-1 in NUREG-2213	****	****	****

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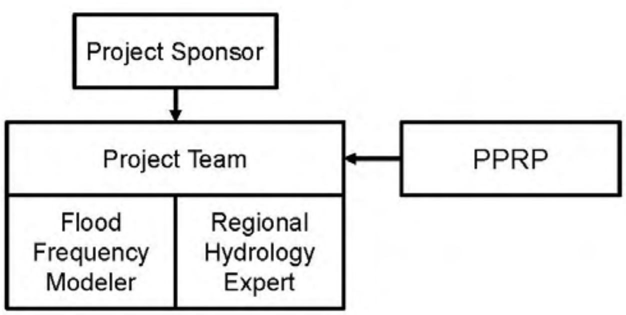
Riverine PFHA Project Structure – SHAC-F Level 1



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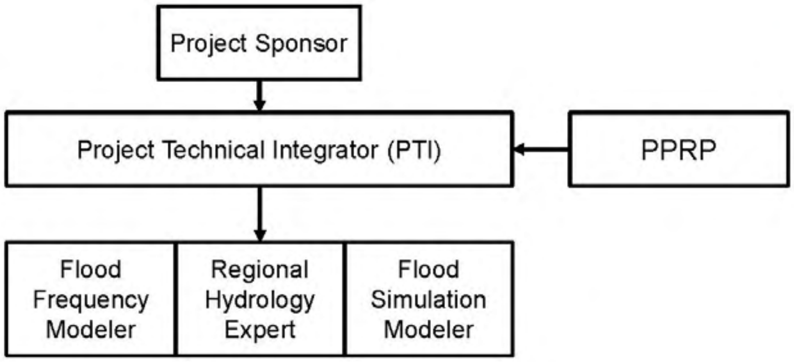
Riverine PFHA Project Structure – SHAC-F Level 2



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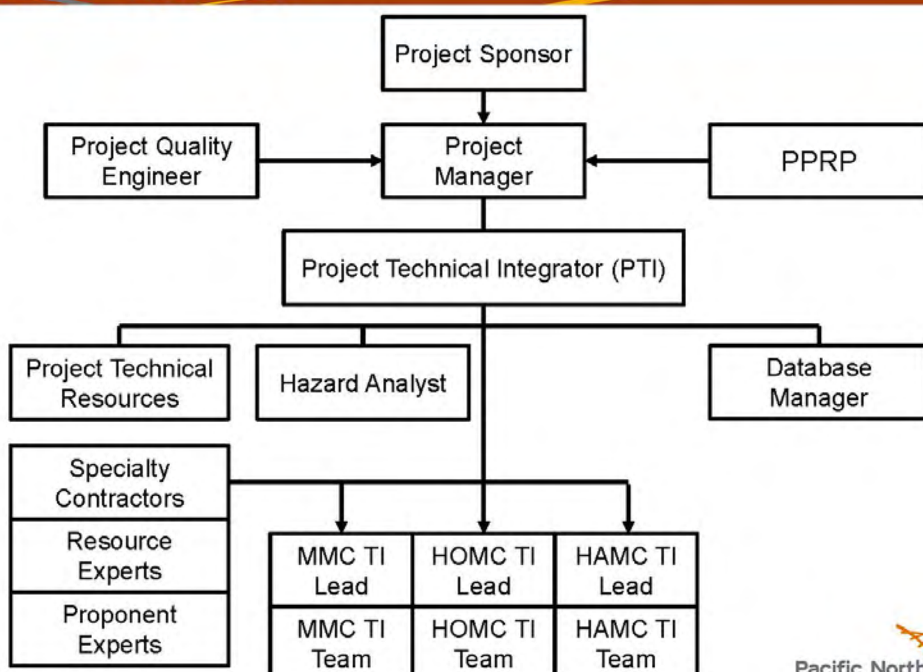
Riverine PFHA Project Structure – SHAC-F Level 3



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Conclusions

- LIP PFHA Virtual Study provided insights that are unique to the flooding problem
- Site-specific nature of flooding requires careful consideration of level of effort for PFHA
- Tying SHAC-F levels to purpose of the assessment is needed
  - Proposed SHAC-F Levels now align with NRC regulatory needs and are consistent with updated SSHAC guidance
  - Proposed riverine PFHA project structures for the three SHAC-F levels are being developed

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Questions?

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3.3.9.2.3 Questions and Answers

Question:

This is Fernando Ferrante with EPRI. You had a suggestion to redefine the level one in SHAC-F to be used for significance determination processes and I think that some interesting insight into the potential benefits and challenges this process can have. SDPs are fast and furious risk assessment types of things and unless data is available, and we say for particular issue, you have paleoflood, you have the availability of complicated models… one of the conclusions may be: if the driver is the one-million-year flood, you don't have any insights that are very explicit qualitative in size. And maybe that's one insight of the process: we've got the kind of thinking that you guys are applying in terms of the SDP or is that kind of preliminary at this point?

Response (Prasad):

It is slightly preliminary at this point. But the assumption is that you would have data that you can quickly collect, and you would be able to do at least the flood frequency analysis relatively easily and quickly. There are methods available now with the Bulletin 17 C and related tools available that could be quickly operationalized and used. But I do think that there is a need to have some of this data centrally compiled and some of the database stuff that we were talking about, that INL was talking about, I think there is a potential for linking through that or an NRC analyst or even an industry analyst to go there quickly get that data which has already been compiled and you don't have to go and dig in into research papers and contact people to get that data. That would speed up the process.

Response (Ferrante):

Well, I think my suggestion would be looking at some of the past SDPs that happened and see how this expert panel, you know 'tiger team', will be able to gather information and have helped some of them.

Question:

I have some experience designing a SHAC study and when the project sponsor got the estimate, they ran a million miles away and it never happened. But, in putting this proposal together it struck me that if others have done a similar project in the flood area and multiple projects have been done, to some extent we'd be going down the same pathways. Each site is different, I agree, but there's only so many models and so many ways of looking at different hydrologic processes and so on. So that leads me to the idea: is there a way of somehow streamlining things? Benefiting from other similar studies that have been done?

Response:

Yes. Definitely. If you look at the lower level SHAC and it says use what you have so the idea being that if you have existing studies and people have done some of those studies, you need to bring them in and you don't need to re-perform them. One of the central things about SHAC is when you get in and do a modeling study that shows your bias: What are your experiences? How do you use models? How you use data to come up with an answer? The SHAC process says that you are not acting as yourself, but you are acting to represent the whole community: all different viewpoints that might be brought together. So, in level one, what would happen is that you would go through and doing the review of every study that has been done for that site: is it relevant for that particular site? You would compile them, and you would appropriately rate them. But in cases where models have not been done or you feel that epistemic uncertainty has not been carried out to the extent that it captures the center and the body of the range, then you would have to go out and do that. So, yes, streamlining as far as possible, you would definitely use that

Question:

I'm interested in clarification on expert elicitation and level two and where that comes in between levels 2 & 3. How do you start weighting parameters and models at the level two process with expert elicitation either internally or externally?

Response:

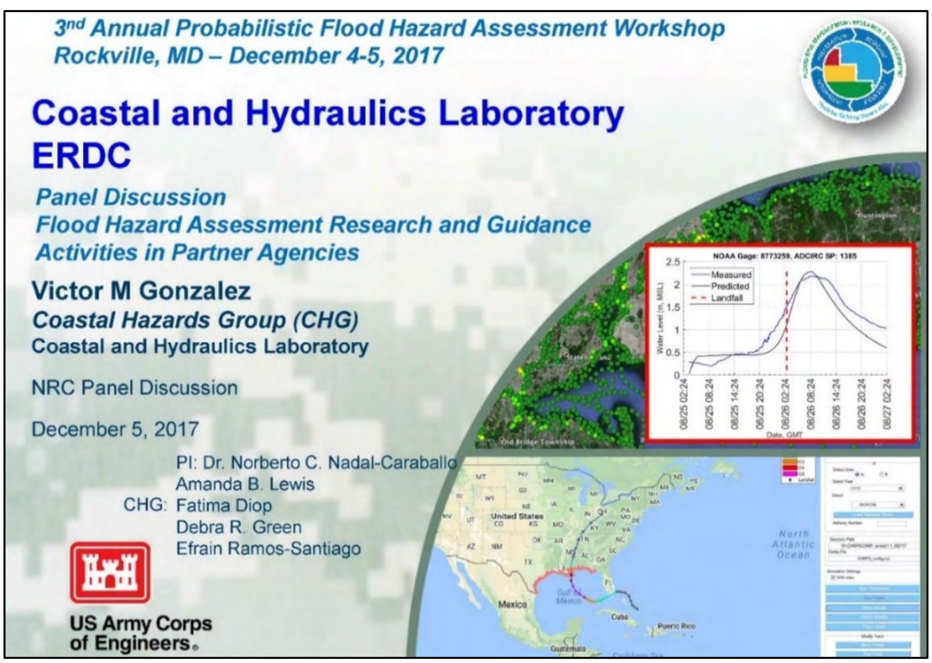
My understanding is that when you weight these models, the committee goes through an appropriately weighted phase and one thing that can help there is that if we can have Bayesian model averaging to show that there are some models which perform better under certain circumstances that could be one way of doing it. Traditionally, model weighting has been done as part of this committee.

3.3.10 Day 2: Session 2C - Panel Discussions

3.3.10.1 Flood Hazard Assessment Research and Guidance Activities in Partner Agencies
(Session 2C-1, ADAMS Accession No. ML17355A076)

Session Chair: Joseph Kanney, NRC/RES/DRA/FXHAB

3.3.10.1.1 US Army Corps of Engineers, Engineer Research and Development Center, Coastal Hazards Laboratory(CHL), Coastal Hazards Group, Norberto Nadal-Caraballo, Ph.D., and Victor Gonzalez, P.E.



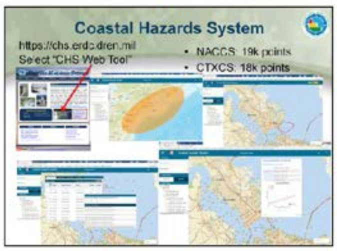
Coastal hazards group
Harbors entrances and structures

Development of probabilistic coastal hazard assessment (PCHA) studies and tools

Risk = **Hazard** × Exposure × Vulnerability

Hazard = Intensity × Probability of Occurrence

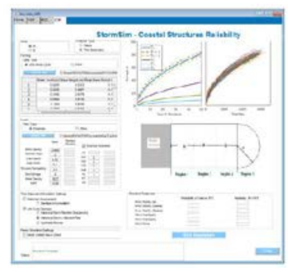
Results:
-Surge
-Waves
-Wind
-Currents



Statistics:
-Hazard curves
-Storm Recurrence Rate
-Storm Relative Probabilities

Tools

StormSim: suite of computer scripts for advanced stochastic analyses.
-PCHA
-Coastal Hazards Prediction System
-Monte Carlo Simulation
-Extreme Value Analysis
-Stochastic Simulation Technique
-Coastal Structure Reliability



- CHS: only national resource for PCHA results and statistics. Supports probabilistic design and risk assessment.
  - Based on regional high-resolution numerical modeling of coastal storms

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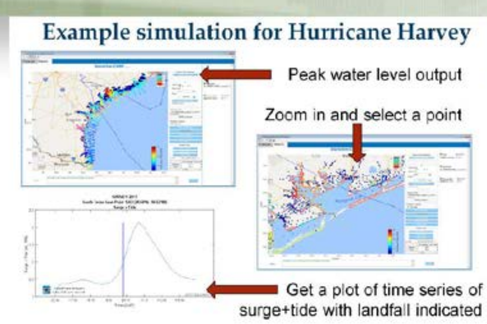
File Name

Coastal hazards group
Harbors entrances and structures

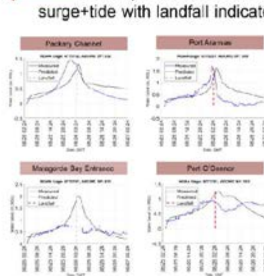
StormSim-CHRP

Coastal Hazards Rapid Prediction

- Provides rapid prediction of coastal hazards for operations and emergency management.
- Uses Gaussian Process Metamodels (GPM) constructed on:
  - CHS high fidelity hurricane-response data
  - Hurricane parameters (latitude, longitude, central pressure deficit, radius of maximum winds, forward speed, heading)
- Hurricane parameters(for an active storm) are read from NOAA 6-hour update web service and used to predict waves and water levels in seconds.



Validation:
Hurricane Harvey
– Advisory 16 –



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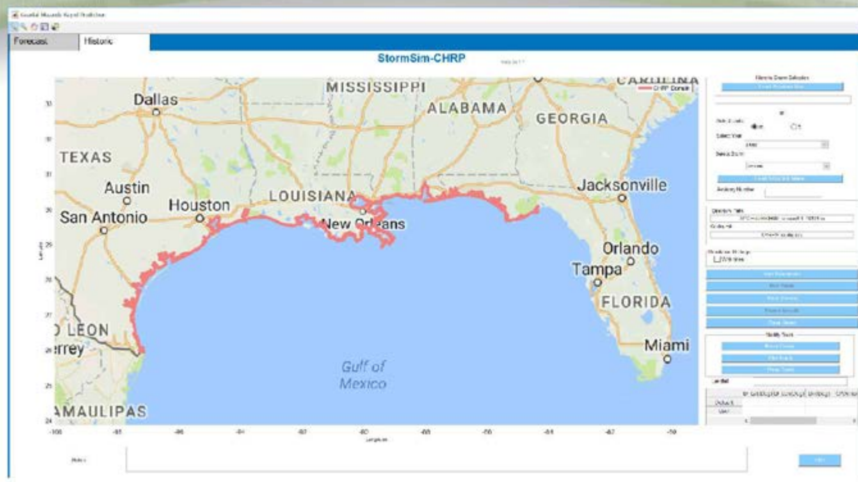
File Name

StormSim-CHRP
Models and Domain



•Predicts surge or surge+tide for 6427 locations in TX, 829 in LA/MS in 0.1 sec, 1100 in AL/Panhandle

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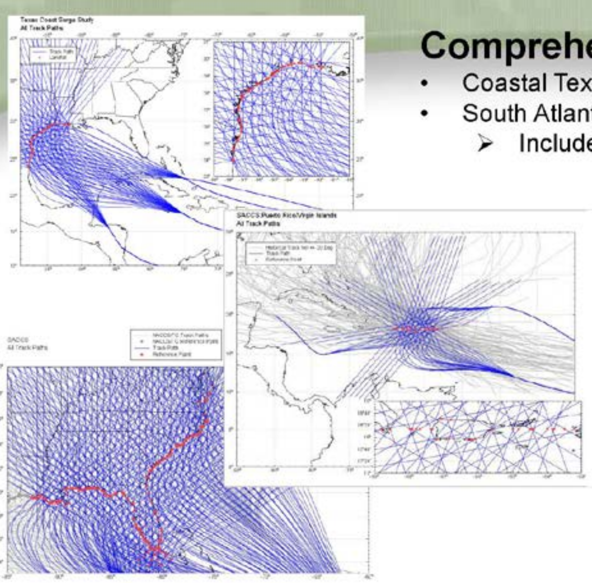
Ongoing Studies



Comprehensive
- Coastal Texas Study (CTXS)
- South Atlantic Study (SACCS)
  - ➢ Includes Puerto Rico & USVI

Region Specific
- 1) Metropolitan Washington, DC Coastal Storm Risk Management Feasibility Study
- 2) New Jersey Back Bays Coastal Storm Risk Management Feasibility Study
- 3) Nassau County Back Bays Study
- 4) Passaic River Levee System Tidal Flooding Study
- 5) Mississippi and Atchafalaya Rivers Flood Event and Structure Operations Assessment
- 6) ACCP Vulnerability Mapping Data (Alabama)

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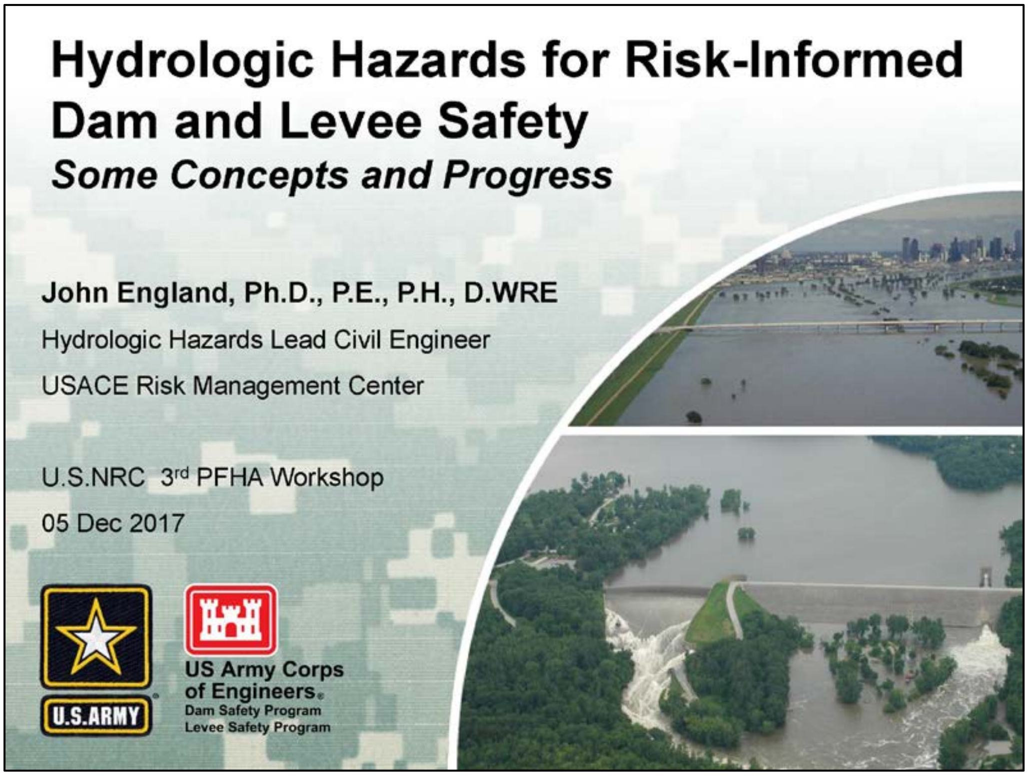
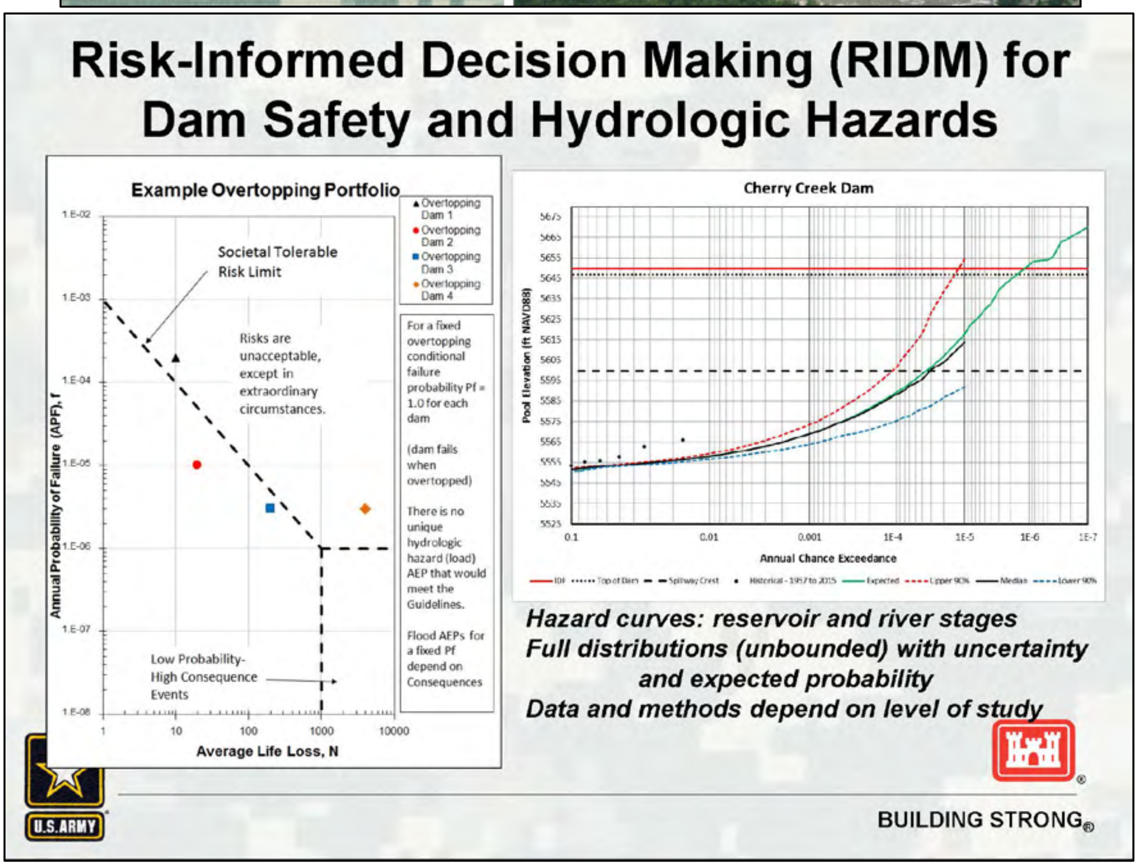
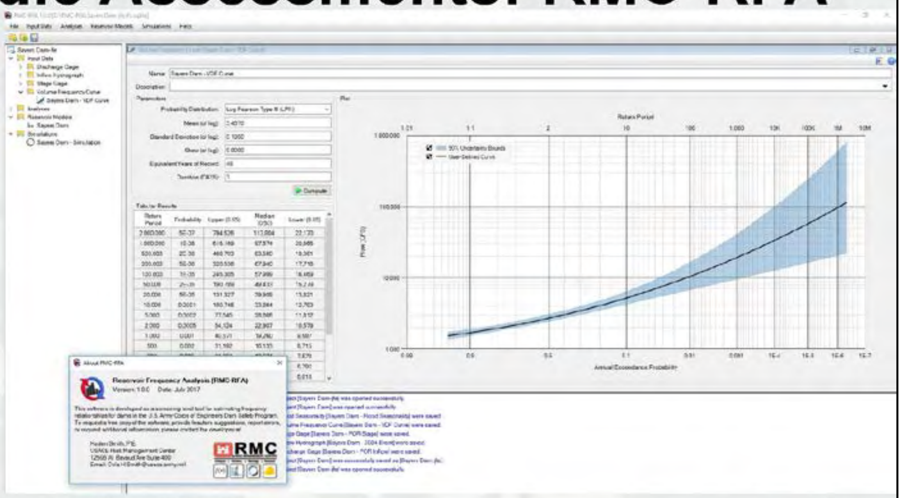
3.3.10.1.2 US Army Corps of Engineers, Risk Management Center, John England, Ph.D., P.E., P.H., D.WRE





Hydrologic Hazards for Periodic Assessments: RMC-RFA



- ***Inflow Volume-based stochastic modeling approach***
- ***Streamflow, historical flood, paleoflood data (inputs from Bulletin 17C)***
- ***Hydrograph shapes***
- ***Flood season***
- ***Initial reservoir level***

- Natural Variability
  - Irreducible, function of the natural system
- Knowledge Uncertainty
  - Reducible through further study & measurement
  - Focus in RMC-RFA is on sampling error

Contact: Haden Smith, RMC

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Paleoflood Studies for SQRA/IES/DSMS

- Ball Mountain Dam
  West River, VT
- Garrison Dam
  Missouri River, ND
- Lookout Point Dam
  Middle Fork Willamette River, OR
- Stillhouse Hollow Dam
  Lampasas River, TX

Studies led by Keith Kelson, Justin Pearce

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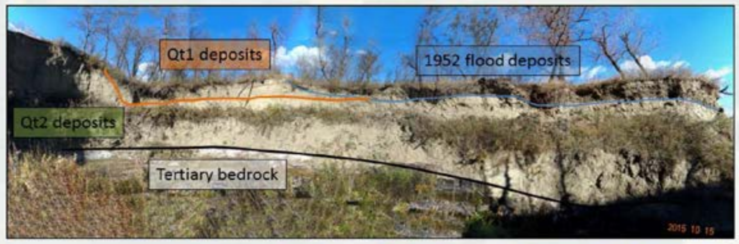
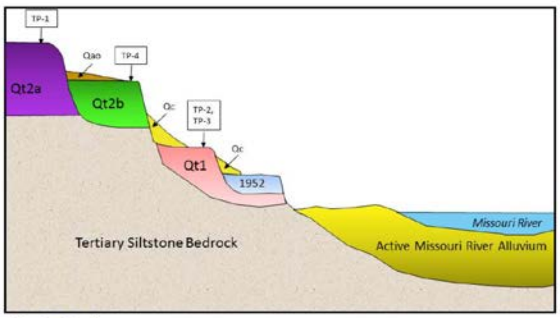
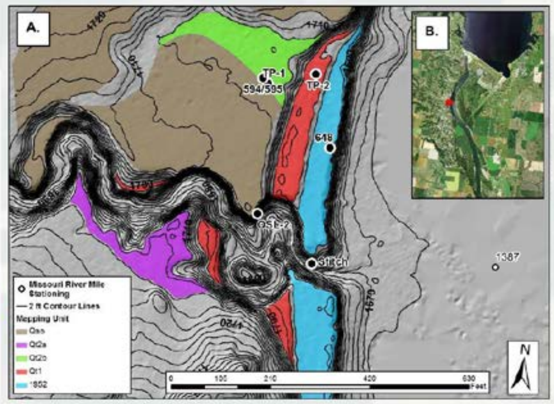
Paleoflood Data Collection - Garrison Dam







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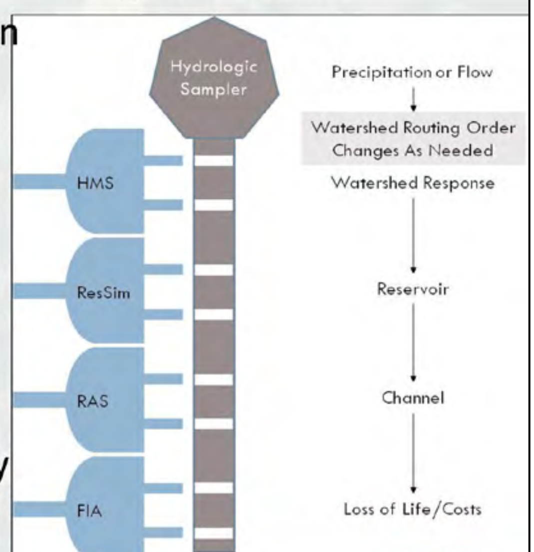
Hydrologic Hazard Analysis IES/DSMS System of Reservoirs: Ingredients

- Extreme Storm Data Collection
  - Spatial/temporal patterns
- Regional Precipitation Frequency Analysis
  - Seasonality
  - Storm typing
  - Stochastic Weather Generation
- Stochastic Rainfall-Runoff Modeling (HEC-WAT)
- Combine with Flow Frequency Curves (HEC-SSP)
- Uncertainty with Expected Probability Curves



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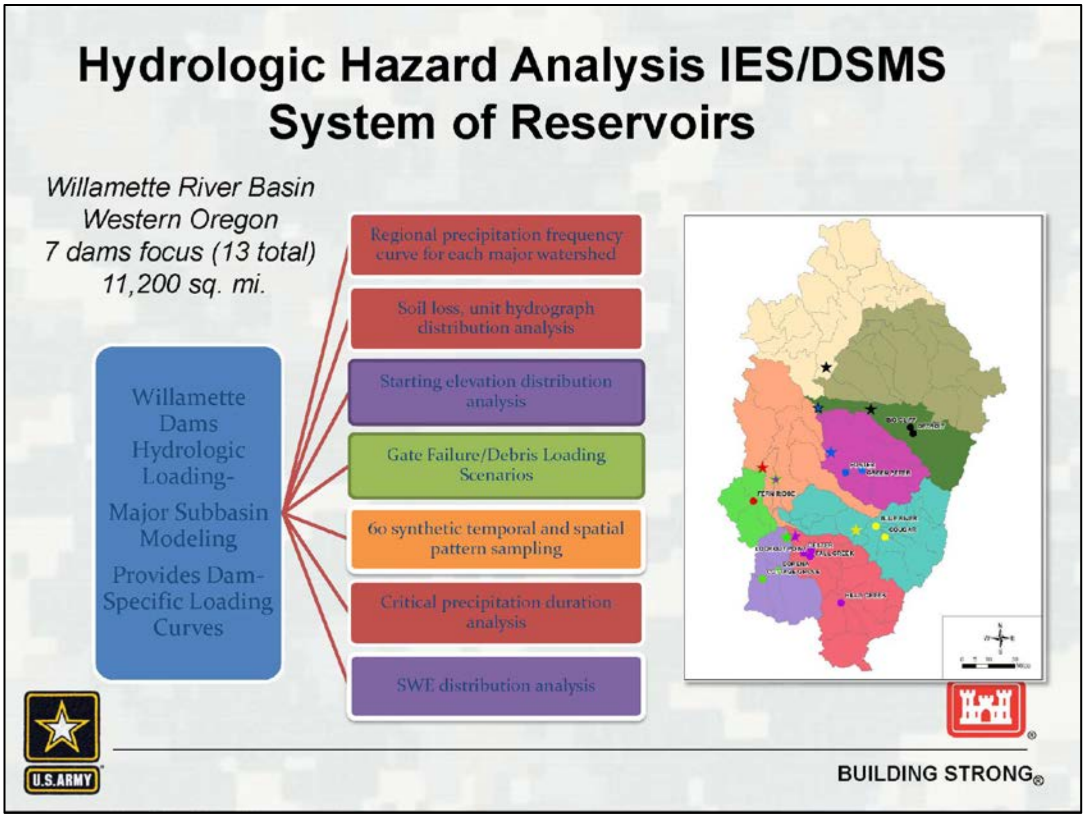


3.3.10.1.3 Federal Energy Regulatory Commission (FERC), Office of Energy Projects, Division of Dam Safety & Inspections, Kenneth Fearon, P.E

SSHAC Seismic Fragility Analysis

- Wanapum Dam on the Mid-Columbia River has a river closure embankment with liquefaction issues.
- A SSHAC fragility analysis is being conducted to evaluate the risk and uncertainty of failure of this dam section
- Currently the second SSHAC workshop has been held and second Technical Integration team meeting is schedule for early January

2

Risk-Informed Decision-Making Program

- Draft Guidelines issued March 2016
  - 4 Policy Guidance Chapters
  - 6 Technical Methodology Chapters
- Two additional RIDM pilots are being conducted in Michigan and California
- Both have hydrology and hydraulics issues.

3

Risk-Informed Decision-Making Program

- Working on a simplified hydrologic model for our Semi-Quantitative Risk Analysis (Level 2) program.

- This program (still in draft) is intended to provide a somewhat conservative result for flood frequencies out to 0.00001 and greater AEPs

4

RIDM Evaluations

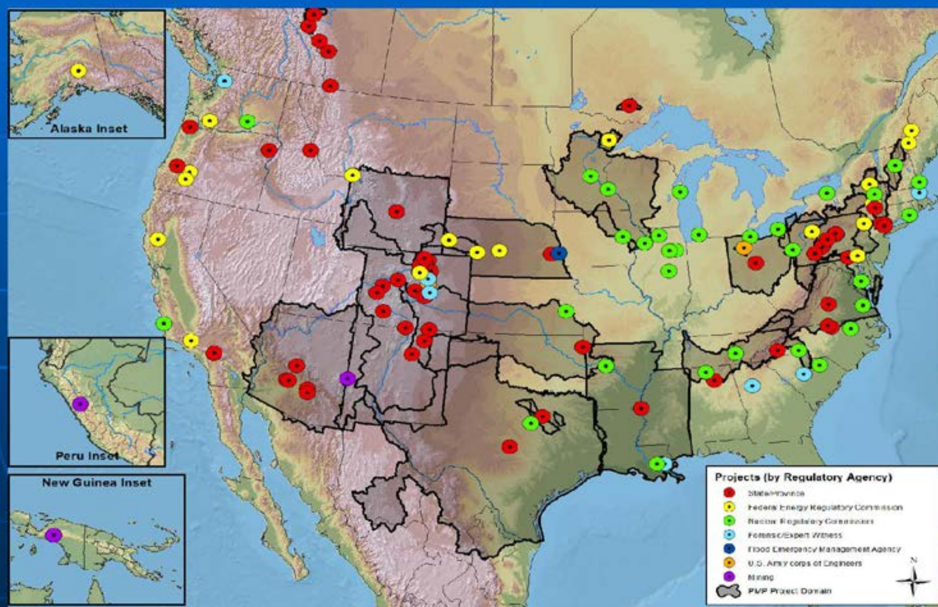
- In both pilots, the uncertainties associated with the structures are more likely to influence decisions about the dams than those associated with the hydrologic loading

- For this reason, further calculation of hydrologic uncertainties are not likely to be useful

- Each FERC regulated dam is unique, so other situations could require a more rigorous evaluation of uncertainty.

5

State SSPMP Studies



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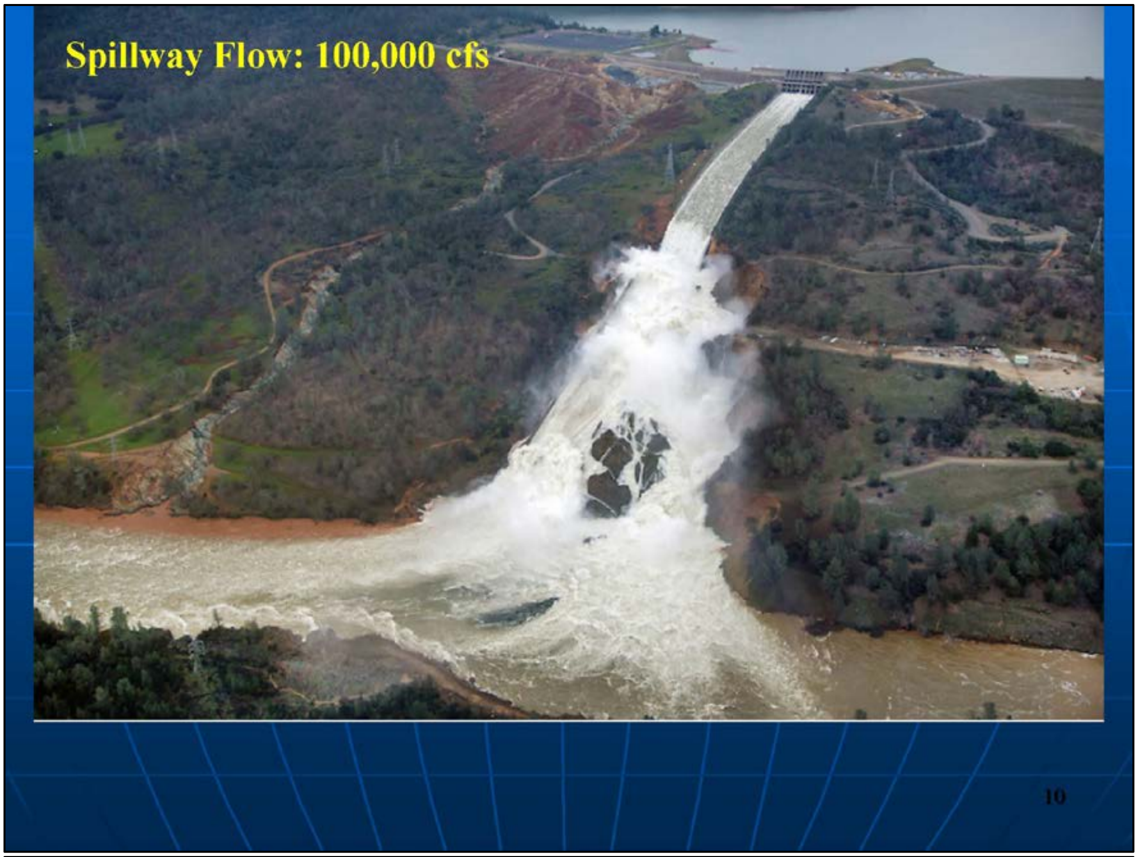
Oroville Dam

7


Prior to February 2017
February 2017
9


Spillway Flow: 100,000 cfs
10

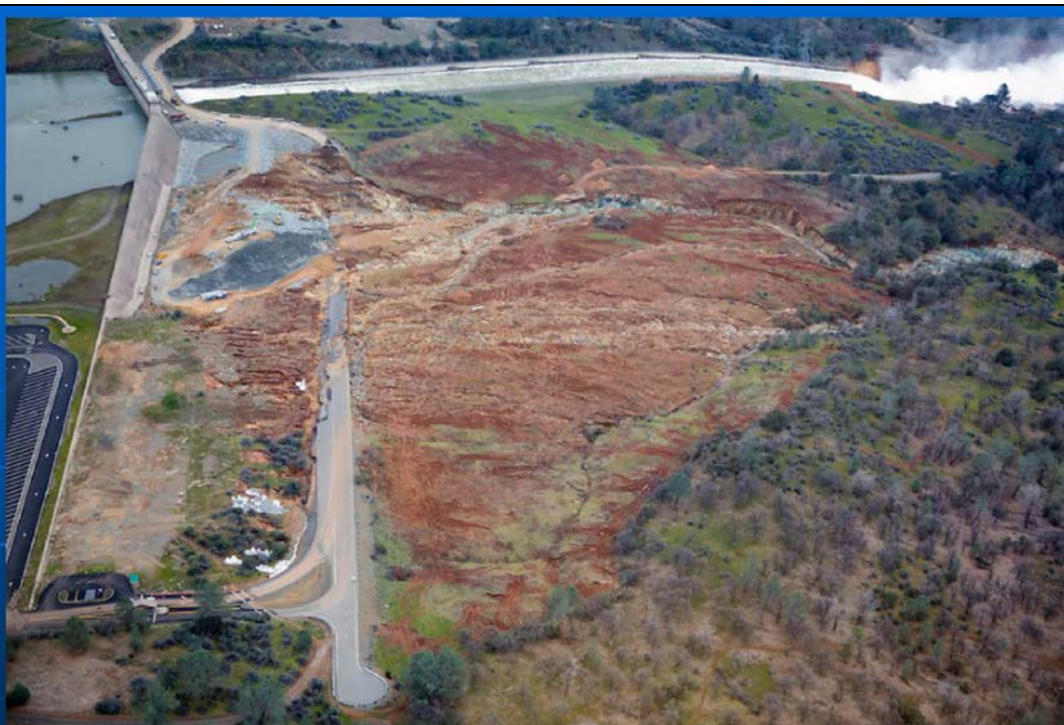

11


12


13

Nearly 1.8 million cy of material eroded and deposited into the Feather River

15



Emergency spillway erosion as the result of 12,600 cfs discharge

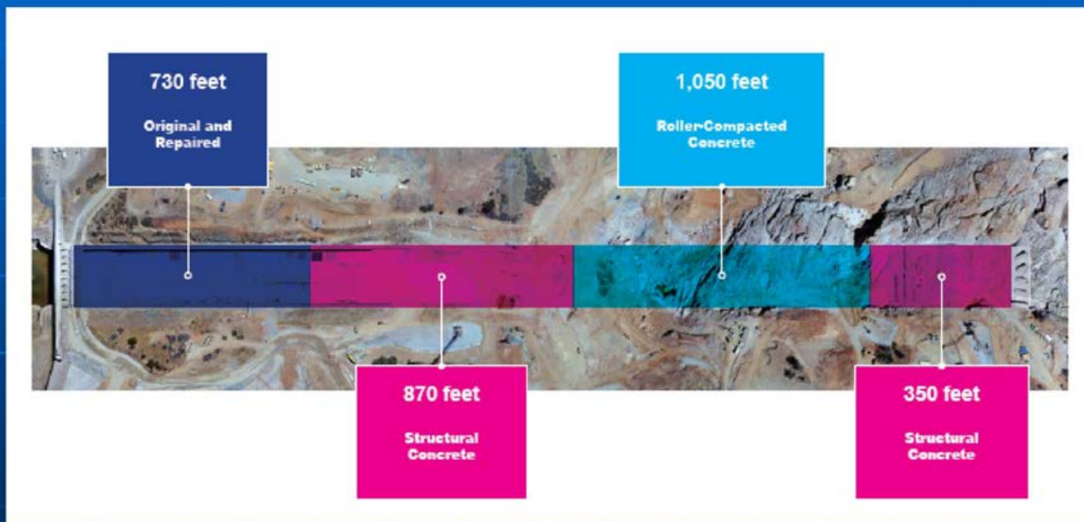
16

The Work

- Spillways contract awarded to Kiewit Construction on April 17, 2017
- Interim requirement was to be able to pass service spillway flows by November 1, 2017
- Final completion by November 1, 2018
- Bid amount = $274 million

18

By November 1, 2017



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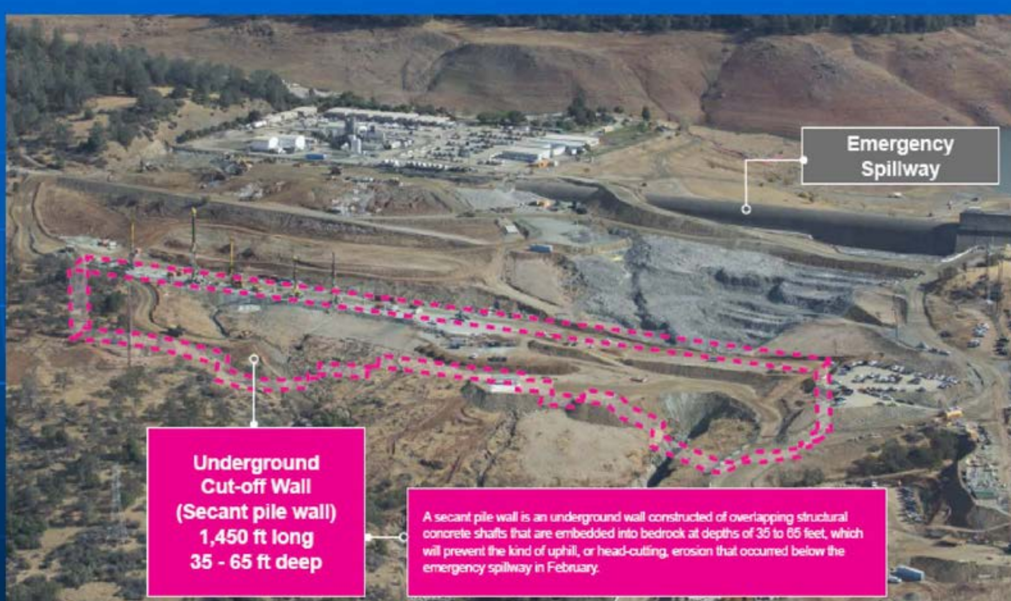
Replace Service Spillway Chute

20

Service Spillway Progress

21

Emergency Spillway



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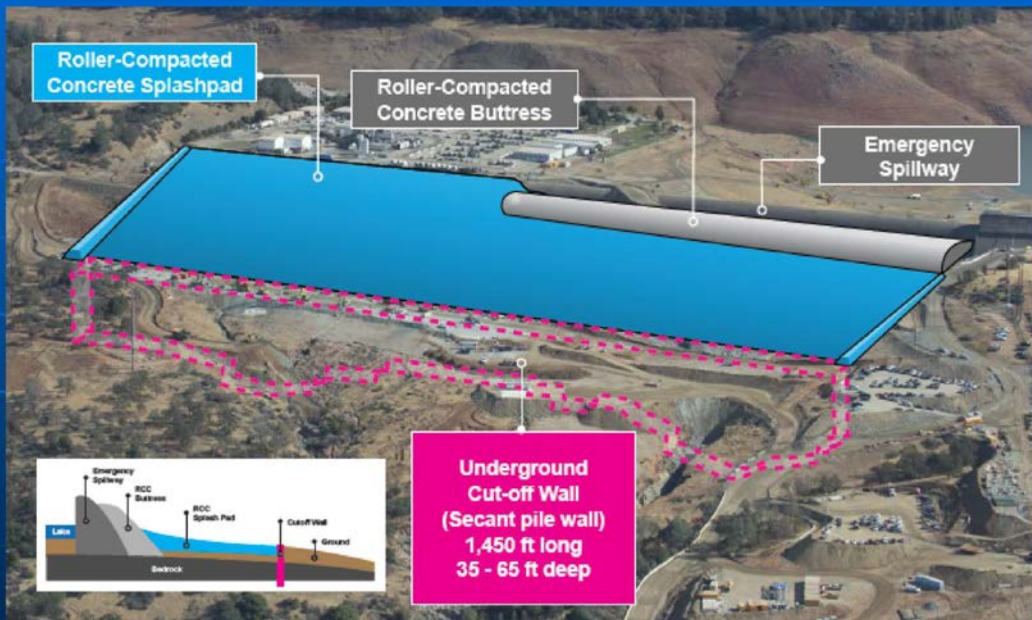
Emergency Spillway



23

Summary of Significant Work Items

- 50,000 cy foundation concrete
- 30,000 cy structural concrete
  - 264 concrete slabs
  - 78 wall panels
- 3,000 sy shotcrete
- 340,000 cy RCC
- 220,000 cy rock excavation
- 605 secant piles (still in progress)

24

Enough concrete to place a 4-foot-wide sidewalk 4 inches deep from Washington, DC to Cheyenne, WY

Summary of Work Effort

- 5 months duration
- Over 1000 construction workers a day at the peak
- Almost $3 million dollars a day over the last 2 months
- $220 to $235 million construction in costs so far
  - That's a 3-year project anywhere else!

26

3.3.10.1.4 U.S. Department of Energy, Office of Nuclear Safety Basis & Facility Design Department of Energy, Sharon Jasim-Hanif, Ph.D.

EHSS
Office of Environment, Health, Safety and Security

Natural Phenomena Hazards Analysis and Design Criteria for DOE Facilities

Sharon Jasim-Hanif, Ph.D.
U.S. Department of Energy
Office of Nuclear Safety Basis & Facility Design (AU-31)

December 2017

1

Overview

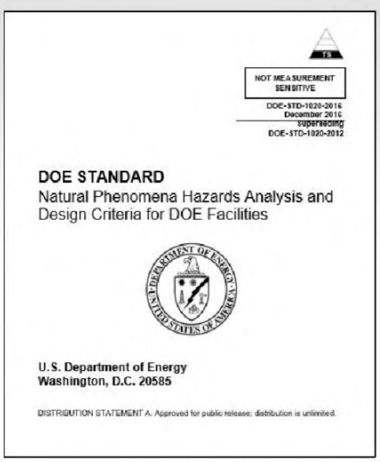
- DOE NPH Program Summary
- DOE Standard NPH Requirements
- DOE Flood Design Criteria & Guidelines

NPH Program Summary

- DOE Office: Office of Nuclear Safety (AU-30)
- Mission: Develop & maintain requirements, standards and guidance for DOE facilities (new/existing/owned/leased) exposed to NPHs
- Driver: Established through DOE Order (O) 420.1C, Facility Safety
- Direction & Guidance: Ensure that SSCs will perform assigned safety functions during and after design basis NPH events; provide requirements and guidance in the use of building codes and voluntary consensus standards
- How: Provides assistance, training, communications & support to facilitate effective implementation of DOE's NPH Requirements to assure public & worker health & safety

3

DOE NPH Requirements



NOT MEASUREMENT SENSITIVE

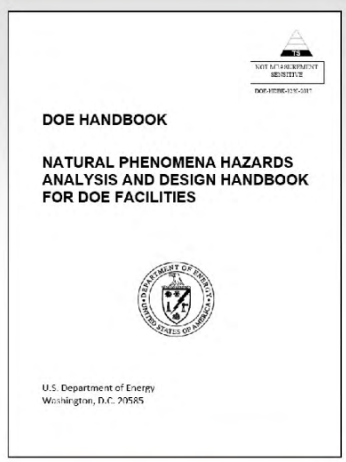
DOE-STD-1020-2016
December 2016
Superseding
DOE-STD-1020-2012

DOE STANDARD
Natural Phenomena Hazards Analysis and Design Criteria for DOE Facilities

U.S. Department of Energy
Washington, D.C. 20585

DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.

DOE Standard 1020



DOE HANDBOOK

NATURAL PHENOMENA HAZARDS ANALYSIS AND DESIGN HANDBOOK FOR DOE FACILITIES

U.S. Department of Energy
Washington, D.C. 20585

DOE Handbook 1220

4

DOE STD 1020/DOE HDBK 1220
Overview

Section 1. Introduction

Section 2. General Criteria for NPH Design

Section 3. Seismic Design

Section 4. Wind, Tornado, and Hurricane Design

Section 5. Flood, Seiche, and Tsunami Design

Section 6. Lightning Design

Section 7. Precipitation Design

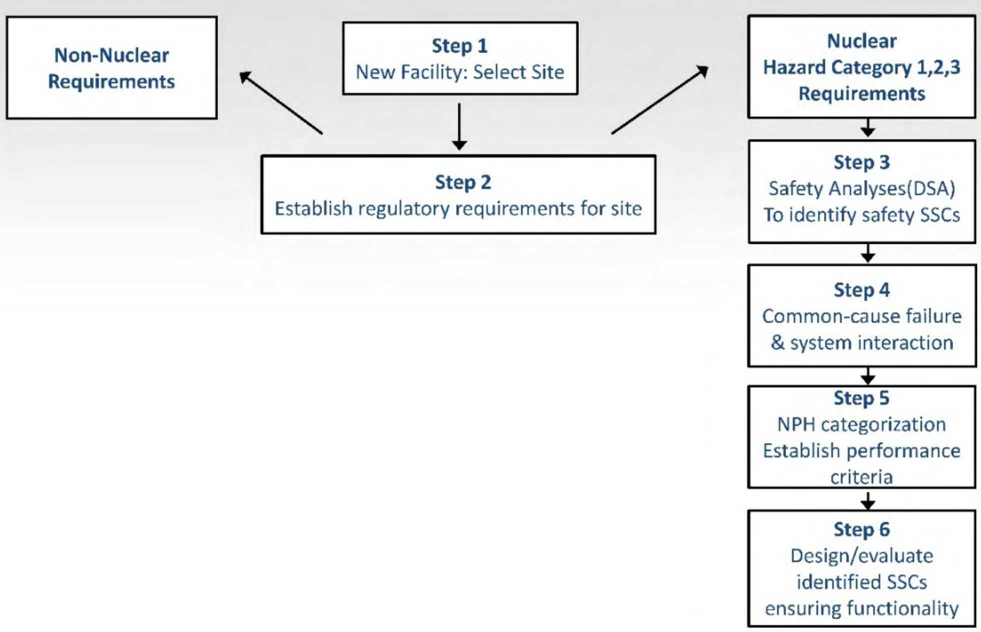
Section 8. Volcanic Eruption Design

Section 9. Evaluation and Modification of SSCs in Existing Facilities

Section 10. Quality Assurance and Peer Review

5

NPH Analysis & Design
Overview



6

Flood Design Criteria & Guidelines

Section 5:

- 5.1 Determine Flood Design Categorization
  - General Approach
  - Return Periods for Design Basis Floods
- 5.2 Perform Site Characterization for Flood-Related Design
  - General Requirements
  - Characterization of Site Hydrological/Meteorological Data
- 5.3 Determine Flood-Related Hazards
- 5.4 Perform Probabilistic Flood Hazard Assessment & Determine Flood Design Parameters
  - Design Basis Flood Level FDC1-2
    - IBC-2015 (II/IV) Requirements
  - Design Basis Flood Level FDC3-5
    - Flood Screening Analysis/Comprehensive Flood Hazard Assessment
    - "Extreme Load" category ACI 349-13 & ANSI/AISC N690-12 criteria
- 5.5 SSC Design & Evaluate of SSCs to Mitigate Flood-Related Hazards

7

DOE HDBK 1220 (Appendix B)

Probabilistic Flood Hazard Analysis

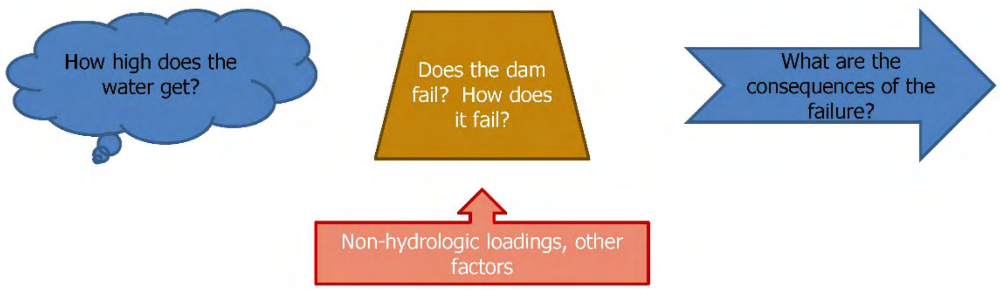
- B.1 Flood Hazards Overview
- B.2 Probabilistic Framework
  - (Overview, taxonomy of Uncertainties, PFHA Results, Flood Hazard Characterization)
- B.3 Probable Maximum Methods
- B.4 PFHA Goals, Elements and Models
- B.5 PFHA for Riverine Flooding
  - (probabilistic aleatory uncertainty model & probabilistic epistemic uncertainty model)
- B.6 PFHA for Flood Associated with Controlled & Uncontrolled Releases from Dams
  - (events & effects of Dam Failures on downstream releases, hydrologic events-extreme precipitation and dam failure, dam failures caused by seismic events, sunny day failures, evaluation of dam break flooding, probabilistic aleatory uncertainty model & probabilistic epistemic uncertainty model)
- B.7 PFHA for Storm Surge Due to Hurricanes, Tropical Storms & Tropical Depressions
  - (analysis, models, probabilistic aleatory uncertainty model & probabilistic epistemic uncertainty model)
- B.8 PFHA for Flooding Induced by Seiches
  - (models, probabilistic epistemic uncertainty model)
- B.9 PFHA for Flooding Due to Tsunamis
  - (model, probabilistic aleatory uncertainty model, probabilistic epistemic uncertainty model)
- B.10 Potential Flood Damage to SSCs
  - (submergence, hydrostatic loads & hydrodynamic loads)

8

3.3.10.1.5 Tennessee Valley Authority, Gabriel Miller

Why should we care about flood hazards?

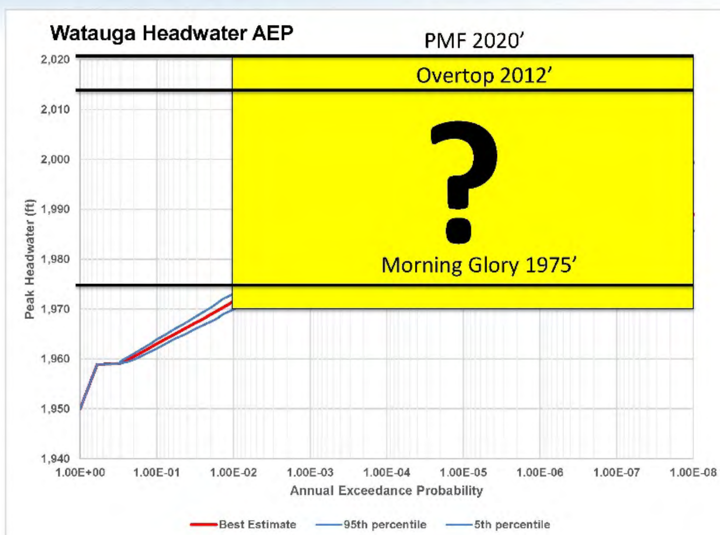
- Risk consists of
  - Loading (Hydrologic hazard curves)
  - System response (Does a dam fail?)
  - Consequences (Life loss, economic, other)



2

Let's use Watauga as an example

- PMF overtops dam by 8'
- However, morning glory has never even been used
- What decisions would a 1:1,000-yr overtopping trigger?
- What decisions would a 1:1,000,000,000-yr overtopping trigger?



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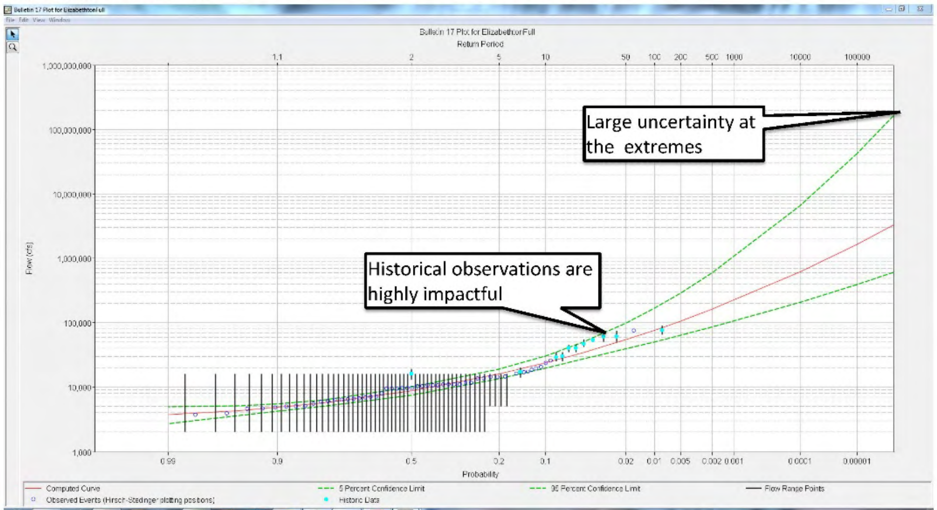
AEP curve for Watauga @ Elizabethton

- AEP Curve developed using annual maximum streamflow
- Done with HEC-SSP



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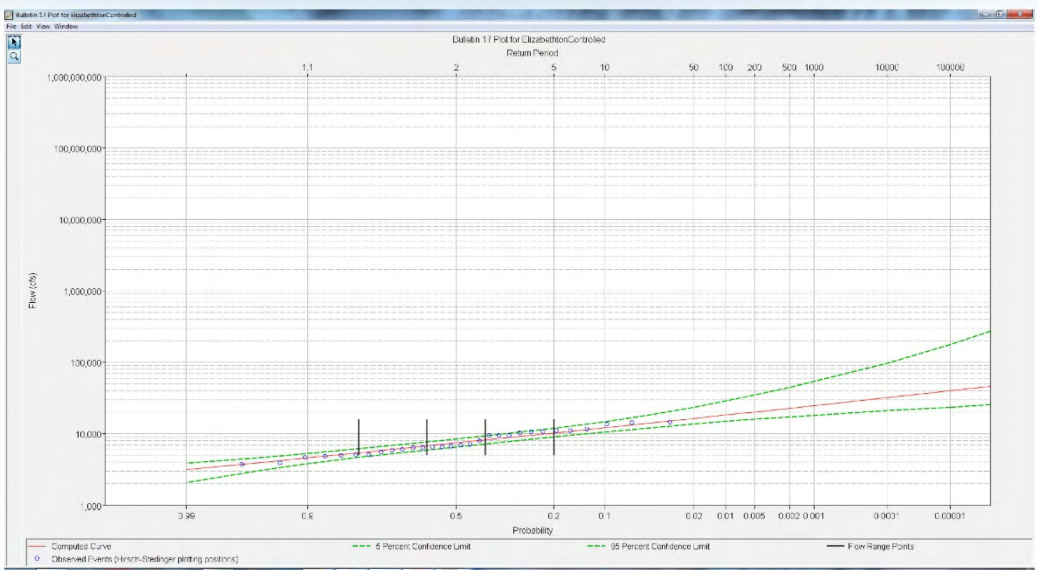
Statistics for only controlled years



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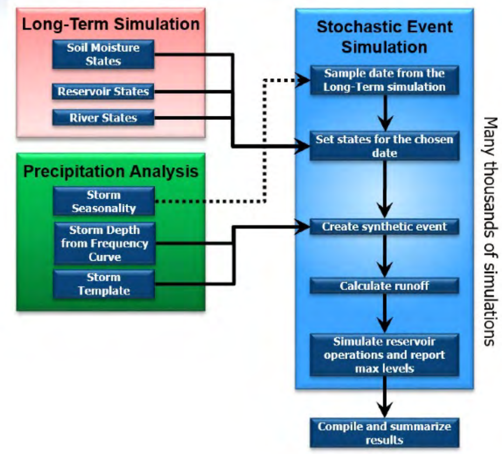
TVA PFHA System

- For each storm type:
  - Sample a date
  - Sample starting states from the long-term simulation
  - Sample storm depth from rainfall frequency maps/stats
  - Sample a storm template, scale to depth and place randomly
  - Calculate runoff
  - Route flow
  - Capture statistics



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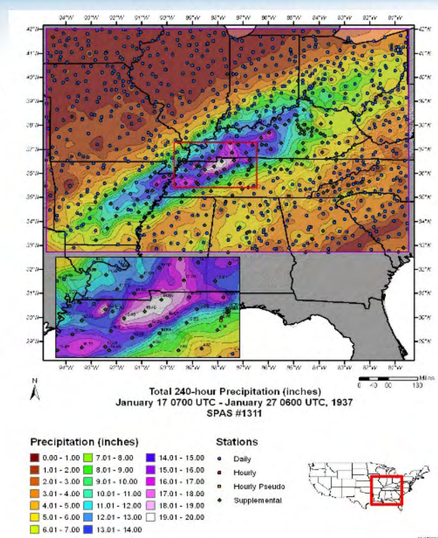
Precipitation Inputs

- Observed storms transposed, scaled and placed randomly over the basin.
- Storm split into types
  - Big winter frontal storms (MLC)
  - Summer thunderstorm complexes (MEC)
  - Tropical storm remnants (TSRs)



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Bonus of storm Typing

- We are extrapolating to very extreme levels, so reducing uncertainty is very important
- Separating storm types helps reduce uncertainty a lot, because each storm type is very different
- At right, is the example of a farmyard. Storms behave in a similar manner.

Mixed Population

Animal #	Species	Weight (lbs)
1	Pig	400
2	Cow	1000
3	Chicken	8
4	Pig	375
5	Cow	1100
6	Chicken	7
7	Pig	390
8	Cow	950
9	Chicken	6.5
10	Pig	420
11	Cow	1150
12	Chicken	7.2
13	Pig	365
14	Cow	1050
15	Chicken	6.9
	Average	482
	Stdev	448

Animal Separation

Animal #	Species	Weight (lbs)
3	Chicken	8
6	Chicken	7
9	Chicken	6.5
12	Chicken	7.2
15	Chicken	6.9
	Average	7.1
	Stdev	0.6

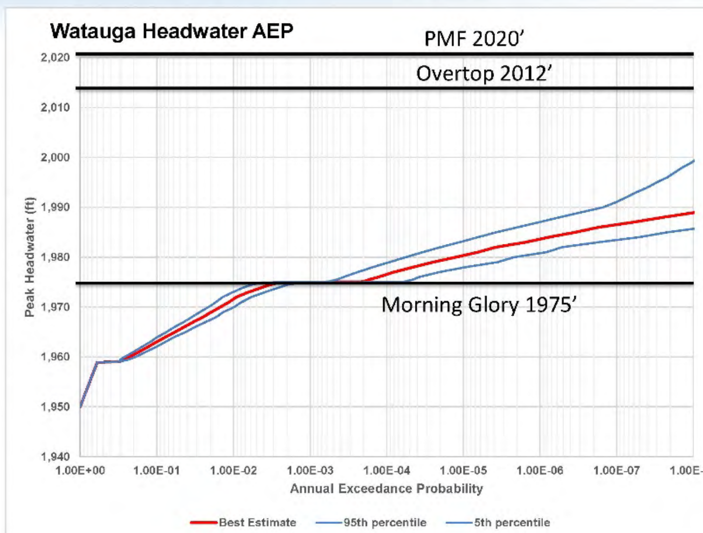
Animal #	Species	Weight (lbs)
2	Cow	1000
5	Cow	1100
8	Cow	950
11	Cow	1150
14	Cow	1050
	Average	1,050.0
	Stdev	79.1

Animal #	Species	Weight (lbs)
1	Pig	400
4	Pig	375
7	Pig	390
10	Pig	420
13	Pig	365
	Average	390.0
	Stdev	21.5

8

Our Results

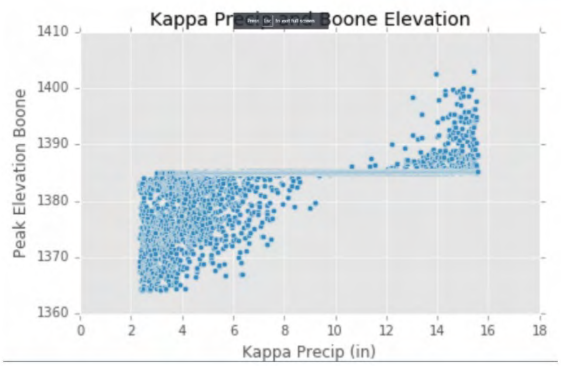
- Likelihood of PMF is REMOTE
- Likelihood of overtopping is REMOTE
- Raising the dam would be a poor risk-reduction measure ($$$$)
- Investing elsewhere would reduce more risk (lives)

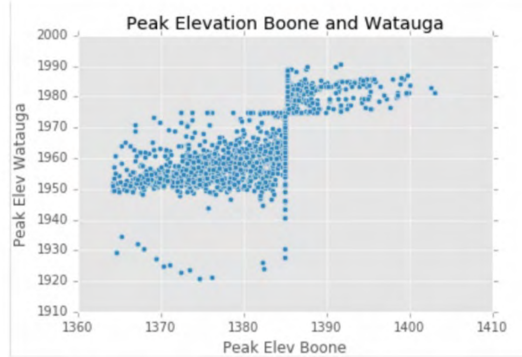


9

Typical insights available

Boone doesn't lose control until *at least* 10" of rainfall





Boone only loses control if Watauga loses control

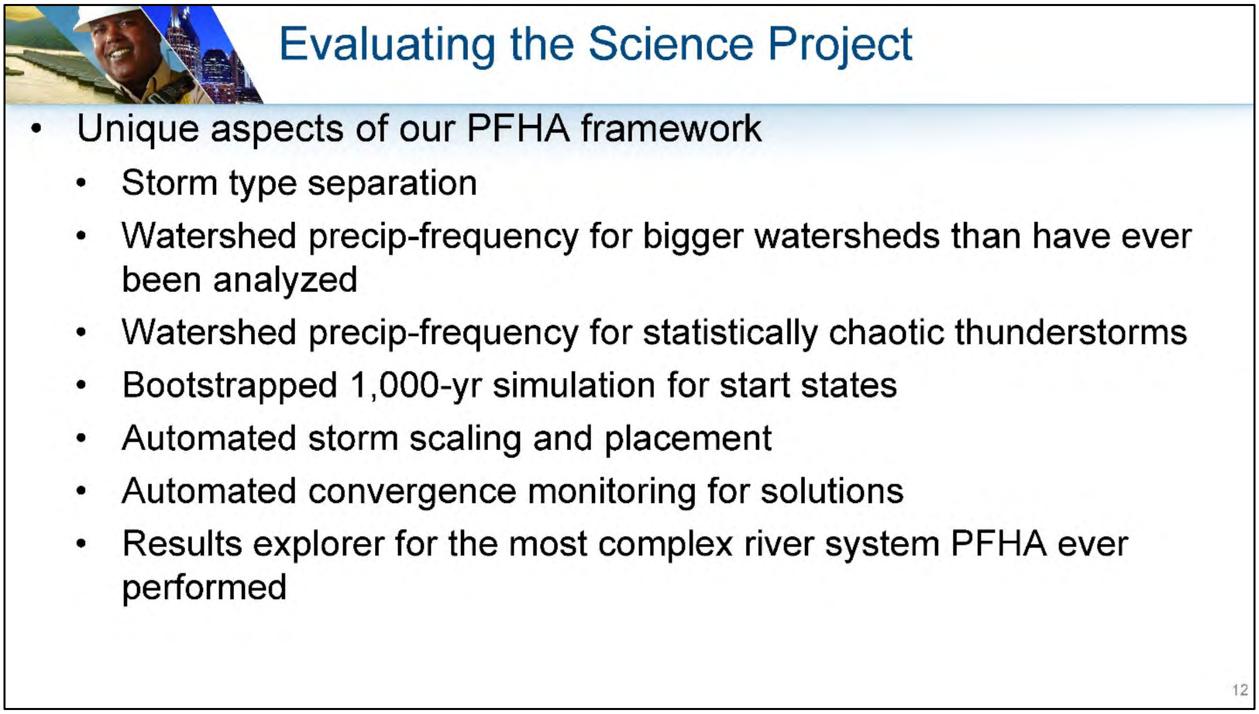
10

Framework Documentation

- Our documentation (available upon request)
  - Overview Calculation
  - SOP and User Manual
  - Point Precipitation Frequency Calculation
  - Methods for Preparation of Rainfall Inputs Calculation
  - Technical Documentation Calculation
  - RiverWare Model Calculation

- Peer Review
  - John England: Main driver behind USBR and national flood hazard methods
  - Dr. Jery Stedinger: Internationally-recognized water statistics expert
  - Review was extremely positive

11



3.3.10.1.6 Discussion

Question:

I'm very interested in what TVA is doing. You said you're doing very intense precipitation analysis for each watershed. Are you making estimates of the problem maximum precipitation for those, and if so, do you have sufficient data and who's doing that analyses?

Response (Gabe Miller, TVA):

Yes, we have done probable maximum precipitation for all of those. I haven't been involved so much in in that part of the project. I know that we've worked with MetStat and MGS a lot for the for the precipitation part of this work. You might talk to Sean. He has been involved in that a lot, but I haven't I wasn't actually involved in that part of the analysis. [Sean: AWA - Applied Weather Associates].

Question:

Joe Wright here with Reclamation and I have a few questions but the sake of time I'll start with Gabe I've heard a few talks yesterday on paleo flood estimates in the Tennessee Valley and I'm just curious to know how your stochastic event flood model, how the results that you're getting from that compared to those paleo flood numbers. Now I realize you have to run it unregulated but…

Response (Gabe Miller, TVA):

Yes, so that question I can answer. That’s something that we still are hoping to analyze. So, we have a lot of that paleo flood information. We have a Naturals model for the Tennessee River. So, the idea is that we will be able to run a lot of our storms through the Naturals model to hopefully match some of the stages and information from those paleo floods and hopefully that should give us a better sense of how our system is performing and also look at some of those paleo floods. So that's still pending analysis for us but something that we have on the docks to do.

Question:

Steve Breithaupt with the NRC. I'm curious: this is again for Gabe. What you're doing is really interesting. So, the question is about your storm templates. Can you describe that a little bit more - about what that includes? Like, I'm particularly interested in multiple peaks, durations… how you included that?

Response (Gabe Miller, TVA):

So, we've taken a lot of storms of different durations for the region and we've come up with gridded precipitation sets for those storms and there are some durations… I'm not sure if we're using multiple peaks on some of them, although we are getting the antecedent conditions before that, so those storms that we've looked at are historical maximum storms from those areas and are then transposed and scaled based on kind of the region and the topography over the locations that were interested in

Follow-up (Breithaupt):

So, it's your understanding that it's basically a single peak storm? Is that what you're saying or…

Response (Gabe Miller, TVA):

I'm going to let Shaun answer that.

Response (Shaun Carney, RTI International):

The basic idea is the largest historical storms that have been run, we took those and analyzed the entire period of the storm. So, some of those are multi peak events that actually occurred historically, or they may be a one bump storm. But the idea is to try to capture the actual variability that's happened historically and in these extreme storms and represent that in the simulation. So, we have a suite of forty different storm templates or something that we can draw from to capture the variability that's happening.

Follow-up (Breithaupt):

Is this information going to be when this is going to be released? A website or something…

Response (Gabe Miller, TVA):

So, we have a lot of documentation. I don't think we're going to put it on a website, but we do have a lot of documentation and information that we can and are willing to share about it. So, if you want to contact or talk to me or one of us at TVA afterwards we'd be happy to share that information.

Question (Joe Wright, Reclamation):

This time I have a question for Ken, but it could be directed to all of you. This involves construction risks and it's something that we wrestle with that at Reclamation and I'm just curious how you might deal with interim construction risks, in reference to some of the large floods that can occur while the construction site is, so to speak, vulnerable to the more frequent floods?

Response (Ken Fearon, FERC):

I found at Oroville that a lot of effort went into looking at start data for rainfall events and, pretty much, the target was June 1 to November 1. Because historically California doesn’t get rain June 1st to November 1st. So, for this one, and, you know, like it or not, things had to be fixed. And so, we didn't have an option to spend a lot of time and say we're going to do analyses after analysis. I mean it was looked at. Everything was done fast. But that's why it was built the way it was. There was no way you're going to rebuild this entire structure in a couple months. So, you know you have sections that are final you have sections that are going to be replaced.

Response Question (Joe Wright, Reclamation):

Orville might be a bad example or an extreme example there. But what if you have something that spans a three-year or five-year construction period.

Response (John England, USACE/ Risk Management Center (RMC)):

Now we have those in the Corps of Engineers and, as Joe knows, in Reclamation so I will point to interested folks to the joint publication by Reclamation and the Corps of Engineers Best Practices in Dam and Levee Safety Risk analysis. We have a course that's usually every year with documentation that's periodically updated and one of the sections in that is on construction risk. So, you'll find out if you look on the web and do some searching that one of our facilities in Houston had an embankment exposed; working on essentially a filter blanket during [Hurricane] Harvey. So, the choice in the risk analysis is focusing on what level of cofferdams do you design to protect the particular area of interest. So, there are procedures to do construction risks when you're doing structural modifications for existing dams. It's not a straightforward and there's lots of areas or improvements.

Question (Tom Nicholson , U.S. NRC):

I have a quick question for Victor. I'm very fascinated. You were talking about the probabilistic coastal hazard assessment and you said that you had looked because of Hurricane Harvey at the Galveston district. One of the questions we had of the weather district (we went and actually met with them about a month before that) and the things we were concerned about is that not only do you worry about storm surge, but the accumulation of rainfall. So, the areas in the interior: they referred to it as fresh water flooding as opposed to saltwater flooding. I'm interested in what kind of insights you got before and after that storm with regard to rainfall amounts and flooding due to that, especially the long duration of that hurricane over Houston. What kind of information you have for us on that?

Response (Victor Gonzalez, USACE/CHL):

Well, for the lab it was a big eye-opener and, I know for a fact, that now other branches in the lab, the ones involved in hydrology, are actively engaging in research in this area. That's one of the research areas we want to expand because at some point we need to somehow include precipitation on our hurricane models, but as of now, it it's not included.

Question:

Not to pick on you, Victor, but I think you're talking about synthetic storm generation as part of this East Coast risk assessment / risk management process. My recollection is a few years ago people were talking about East Coast tsunamis and I was wondering how tsunamis fit into this risk management picture, if at all.

Response (Victor Gonzalez, USACE/CHL):

No, it’s separate. I mean, the forcing, the response that we're looking at is completely different.

Response Question:

I understand the different mechanism. I’m talking more programmatically: who's got the ball? I

Response (Joseph Kanney, U.S. NRC):

NOAA and USGS collaborate to have a tsunami warning system. And then NOAA has developed several tsunami modeling systems.

Question (Joseph Kanney, U.S. NRC):

I have a question for Sharon. You mentioned that your guidance has developed over several years: you're in version 5. As that handbook has evolved and, you group has several projects, like the waste treatment plant, which has been under construction for many years. What happens when you revise your guide to facilities like that that are they're still under construction? At NRC we have this concept of back fit with our licensees: we have to do a cost-benefit analysis to show that changing the standard will have a significant safety benefit before one would go back and look at older facilities or facility you've already made a decision about. How do you handle that?

Response (Sharon Jasim-Hanif, DOE):

So, we have a similar process except that it depends on the contract. So, if a site has a contract: it depends on the year of the design. For example, with this 2016 update, most of our sites have not incorporated the 2016 and they still they have to work within the policy document that are within their contract. So, it is in their interest to use the most updated information out there and I get calls about that. And I provide training on the differences between the previous version of the standard and the updated: what changed. But if it's in their contract to use a 2012 version of the standard they are about to use that.

Question (Joseph Kanney, U.S. NRC):

John one question for you. In the paleo-flood studies that the Corps has done have you guys looked at any other methods other than slack water deposits to determine paleo-stages?

Response (John England, USACE/RMC):

So, the questions are on slackwater. I neglected to highlight that issue. I was relying on some of the talks from yesterday. So, we actually are focusing on non-exceedance: both [non-exceedance and slack water). The same thing that would happen at Reclamation. Where if you have a strap terrace in Vermont you have a nice stable surface that's of a certain age and you can tell that it hasn't been exceeded. And then the record between that and, say, some positive evidence of flood is incomplete. So, we try to use both pieces of information. So, it's not just the slack water, but it's those evidence of terraces and longer-term features, maybe eight thousand years in the Ball Mountain case and in the Garrison case a couple thousand years, that the floods haven't reach that. So, there is a limit on the magnitude-frequency relationship.

Question (Joseph Kanney, U.S. NRC):

Victor. One question I had for you is with regard to the storm sim tool. Have you thought about getting results from other people's models to enhance what you all have done (thousands of simulations)? But there's also been collectively thousands of simulations done for FEMA studies, for example. Have you contemplated actually going out and getting other people's results to add to yours to give it more statistical power?

Response (Victor Gonzalez, USACE/CHL):

Yes, and the coastal hazard system has some results from FEMA studies and wherever we can get those results for further modeling we incorporate them in our database. So, yes, we do actively search for that information for other studies.

Question:

Is it available?

Response (Victor Gonzalez, USACE/CHL):

It's online so you're free to access the webpage of the coastal hazard systems and you can download the information.

Comment (Joseph Kanney, U.S. NRC):

Yes, actually here at NRC we've leveraged some of the information from that database to help in some of some of our reviews.

Question (Tom Nicholson, U.S. NRC):

John you had mentioned the extreme storm database collection. Could you tell us the status of that? We know something about it - we actually had a demo about a year ago. The question is what are you doing now with regard to creating the portal and the database so that we can interact with it and then look at a variety of storms? As I understand it, you look at some severe storms and then you ask the question: what is the precipitation distribution associated with that storm and then what was the river responds to that storm? So, if you could give us some insights of where that project is now and how soon that could become available to other federal agencies?

Response (John England, USACE/RMC):

The status is easy. The schedule is a challenge. For background I think on my website if you go search there's probably a presentation I gave last year on this. Chuck McWilliams in Omaha district is a meteorologist in charge of our extreme storm database project with folks spread throughout the Corps and they're working now on upload capability. The database has been restructured to look like the National Levee Database. So, for those of you who are familiar with that you can go online and look at essentially static Maps and download some information. They're essentially grid points - so we'll have essentially this space-time of individual events - like what Gabe was talking about - we're doing the same sort of things and I believe Reclamation has done some similar things with storm patterns and since you store those in a library of the largest ones. Currently, though, the limitation is that it's internal only, so we've just got the protocol and CAC authentication, so people have the capability to upload that information. I would hazard a guess maybe in 18 months we could hopefully open it up to sharing for others to contribute. So hopefully between then, now and then, we could hopefully have it as an open website, just like the National Levee Database, so people can get the information. Resource issues are always a challenge with that one, sorry to say.

Question (Ray Schneider, Westinghouse):

I have a question for Victor. Given the amount of synthetic storms that you can create or have created and the large expanse of areas that you have the ability to basically model storm surge and the various tracking and your ability to do this: Is the intent to develop statistical models to basically come up with the probability of flood surge at various point locations if you need to? To just basically sample all your data - could you put your data with, basically, some kind of a sampling structure with reasonable paths and reasonable locations and at various probabilities of getting certain storm sizes of various types to create something that resembles a synthetic way of creating a probabilistic hazard curve for the coast?

Response (Victor Gonzalez, USACE/CHL):

Yes, the answer is just that the selection of storms is done per study and typically those studies get output set at save-points. So, obviously, as we do more areas of the coast we will get coverage over most of the coast of the United States. We will have the ability to do that throughout the Coastline. But, right now, yes you have the ability to create a probabilistic hazard curve based on the probabilities of the synthetic storms for a particular location.

Follow-up Question:

And that could just be done basically by sampling using your data in your systems and basically moving stuff around?

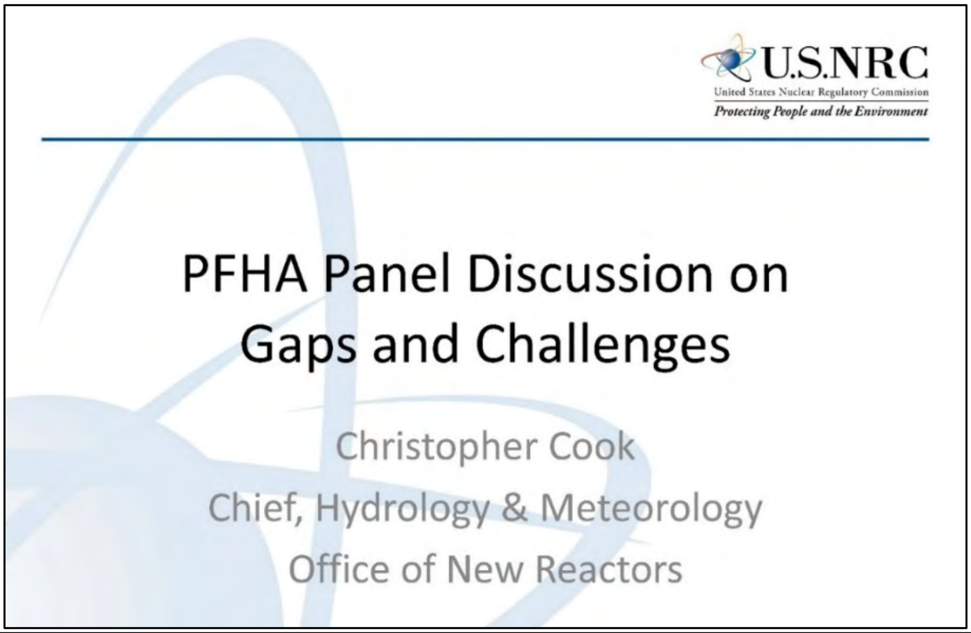
Response (Victor Gonzalez, USACE/CHL):

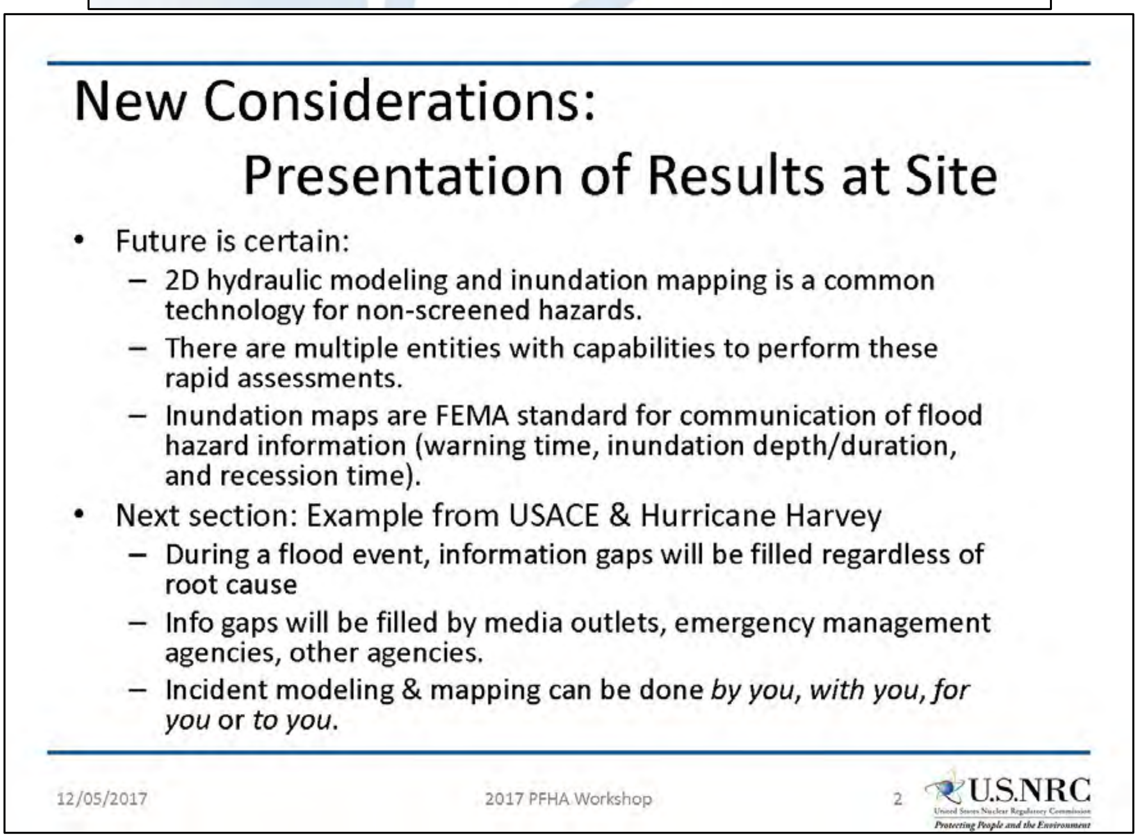
And you have to download the data. We're working towards making this a little bit more user friendly and in order to better distribute this. But, yes, you can download the storm and you can download the relative probabilities of the storms and you can download the corresponding response for these storms. So, you have what you need to do sampling.

3.3.10.2 External Flooding Probabilistic Risk Assessment (PRA): Perspectives on Gaps and Challenges (Session 2C-2, ADAMS Accession No. ML17355A077)

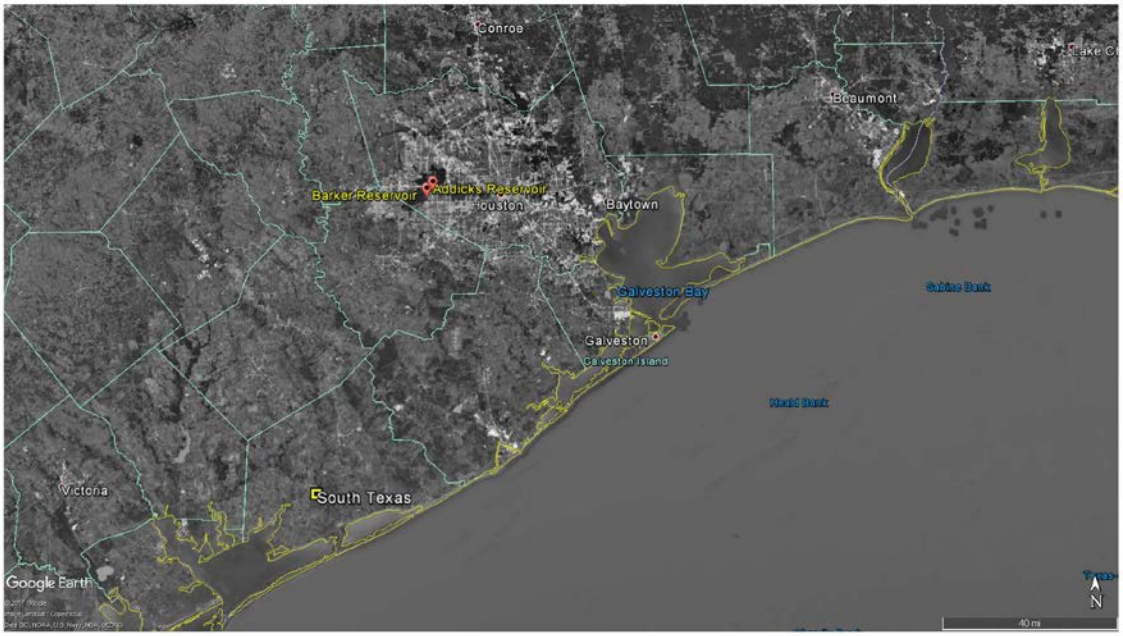
Session Chair: Fernando Ferrante, EPRI

3.3.10.2.1 US NRC, Office of New Reactors, Division of Site Safety & Environmental Analysis, Chief, Hydrology and Meteorology, Christopher Cook, P.E.

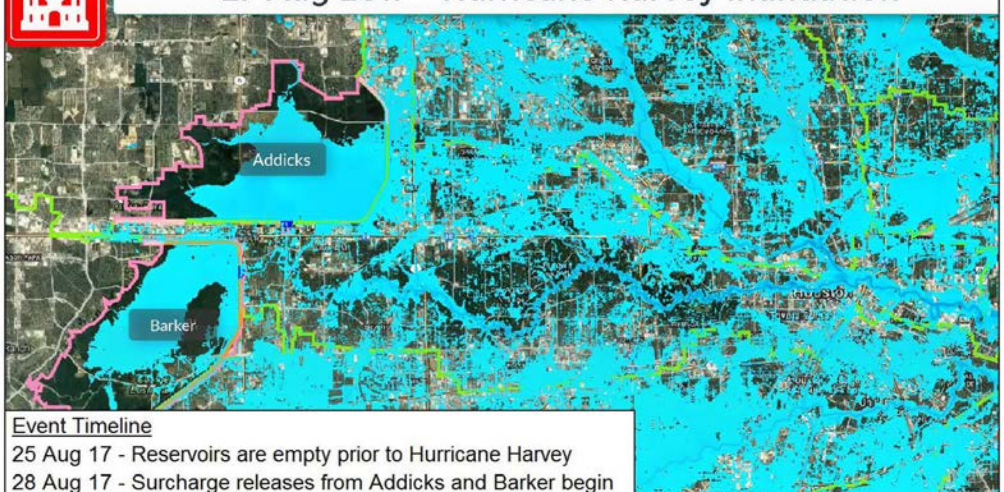




Hurricane Harvey: 10-Day Forecast of Inundation from Barker and Addicks Dams



27 Aug 2017 - Hurricane Harvey Inundation



Event Timeline

25 Aug 17 - Reservoirs are empty prior to Hurricane Harvey
28 Aug 17 - Surcharge releases from Addicks and Barker begin
29 Aug 17 - Water begins flowing around north end of Addicks
29 Aug 17 - Releases increase from Addicks and Barker
30 Aug 17 - Addicks and Barker reach peak elevations
03 Sep 17 - Releases decrease from Barker
09 Sep 17 - Releases decrease from Addicks
15 Sep 17 - Surcharge releases end

Presentation released on Sept 4

Source: https://www.hcfcd.org/hurricane-harvey/flooding-impacts-in-connection-with-the-reservoirs/

Hurricane Harvey: **VIDEO**
Inundation Mapping of Barker and Addicks Dam

PFHA Gap/Challenge #1

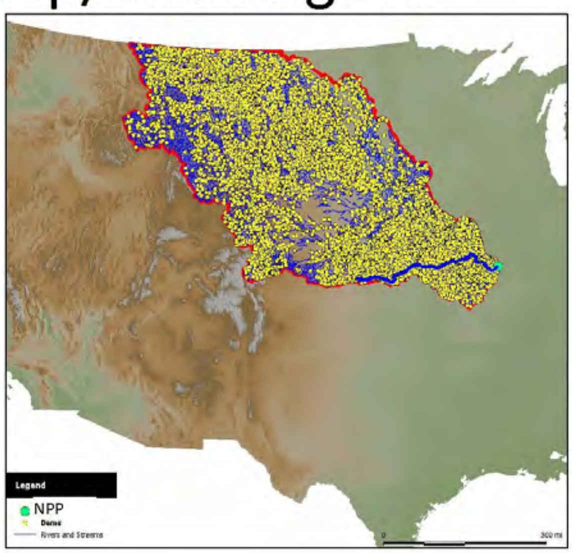
- Static vs dynamic flood hazard information
  - Previously, CDB was reported as a maximum elevation reported to 0.1 ft.
  - Going forward, flood hazards represented as dynamic inundation maps. These show progression of inundation and key associated effects (e.g., water velocity) over time.
  - How can dynamic inundation maps be used to feed PRA models?
  - What does the nuclear PRA community need and is it what the Civil Eng community is producing?

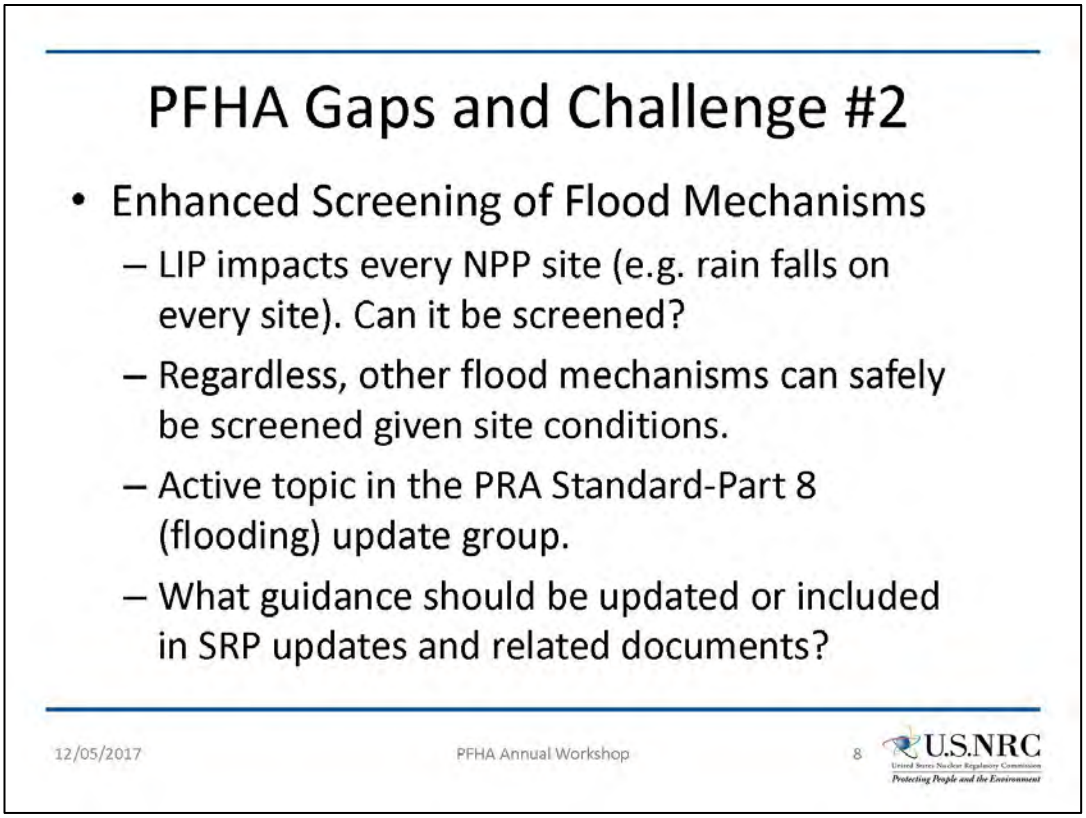
PFHA Gap/Challenge #2

BACKGROUND:

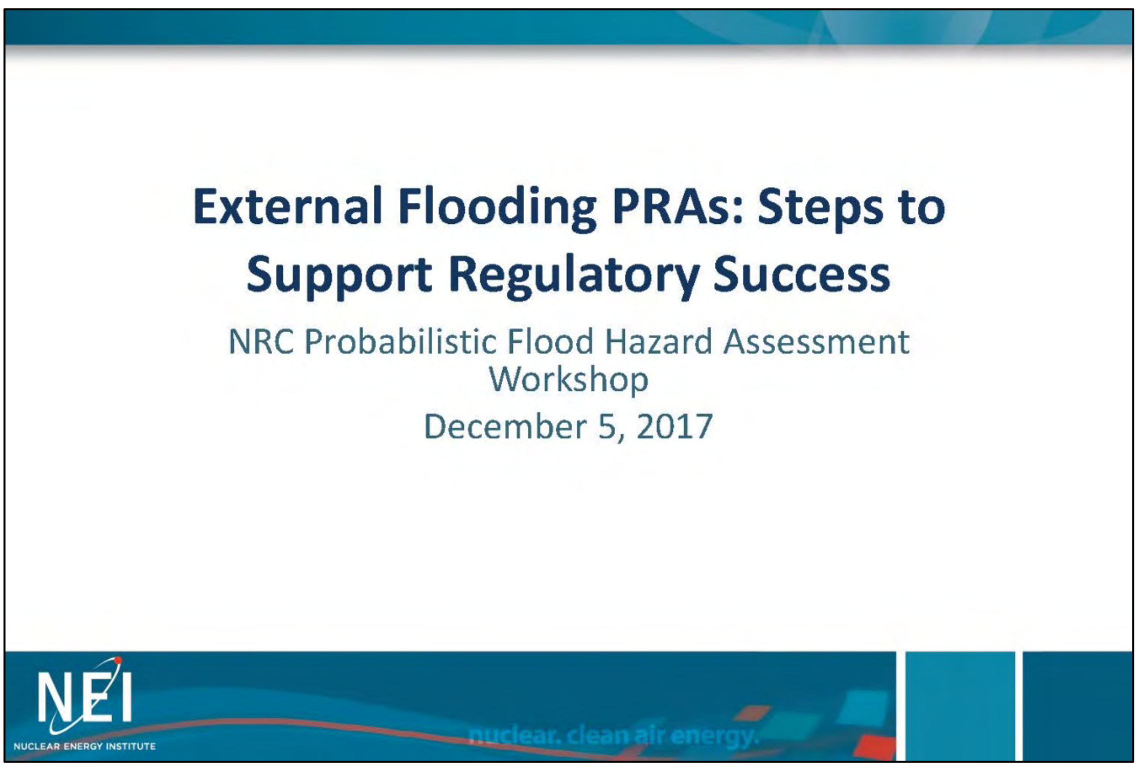
Guidance for screening of upstream dams developed as part of JLD-ISG-2013-01.

- **Figure**: 18,286 dams upstream. Eight of these have a height greater than 250 ft with a max of 491 ft.
- **Figure**: within 500 miles of one NPP (straight line) there are 5,616 dams with a height equal to or greater than 25 ft.





3.3.10.2.2 Nuclear Energy Institute(NEI), Frances Pimentel and Victoria Anderson



Regulatory Application of External Flooding PRAs

- To date, external flooding has generally been addressed in risk informed licensing actions by using bounding assessments
  - Sufficiently supports decision making needs for vast majority of licensing actions
  - Provides assurance that risk estimates are bounded
- While full External Flooding PRAs can provide more realistic treatment, the methods must be sufficiently developed to support this realism

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Fire PRA Lessons Learned

- Modern Fire PRA process developed and piloted in 2005-2008 timeframe
  - Piloting process was piecemeal
  - Framework for Fire PRA development was sound, but individual components retained substantial conservatisms
  - Net effect of individual conservatisms resulted in large, unrealistic results
- Regulatory application of Fire PRAs began prior to addressing issues revealed in pilot process, or full understanding of scope and scale of issues
  - Led to inability to support robust decision making process

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Key Sources of Conservatism to Address Prior to Widespread Regulatory Application

- Lack of information regarding initiating event frequencies for the ranges of interest in external flooding PRAs
- Physical behavior of flooding phenomena for extreme events
- Treatment of dam failures, including combinations
- Consideration of warning time for some hazards
- Fragility of SSCs during flooding event

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How Do We Know We Are Ready?

- Completion of pilot process
  - More than one pilot, addressing all aspects of External Flooding PRA
  - Ability of framework to support development of realistic results in a variety of scenarios
- Alignment of results with operating experience
  - Review accident sequence precursors and compare External Flooding PRA results
  - Comparison of relative risk from other hazards

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3.3.10.2.3 EPRI, John Weglian

ELECTRIC POWER RESEARCH INSTITUTE

External Flooding Probabilistic Risk Assessment

Perspectives on Gaps and Challenges

John E. Weglian
Senior Technical Leader

3rd NRC External Flooding Research Workshop
December 4-5, 2017

External Flooding PRA

- Recall, an External Flooding PRA (XFPRA) relies on a number of parts
  - Determine the applicable external flooding hazards to the site
  - Determine the flood parameters for each applicable flood mechanism
  - Develop a flood hazard curve to determine the frequency of the flood parameters
  - Create one or more scenarios that describe relevant portions of the flood hazard curve for each hazard
  - Evaluate the plant response for each scenario with a PRA model and quantify risks associated with each scenario
- So, what gaps and challenges can be found in these steps?

2

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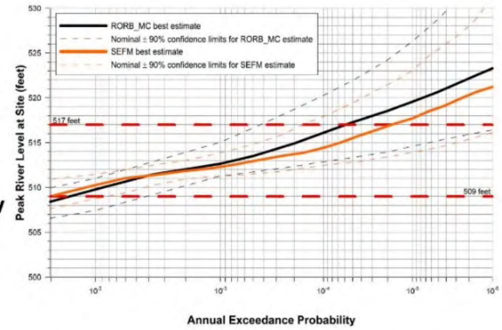
Uncertainty

- Wide uncertainties exist when estimating very low hazard frequencies
  - Paleo data may be helpful in reducing the uncertainty, especially in the 10^{-2}/yr to 10^{-4}/yr range
  - Uncertainties below 10^{-4}/yr will still be large



- Uncertainty combined with cliff-edge effects has the potential to hide significant risk
  - Sensitivity studies can be used to determine if the model results are sensitive to particular aspects of the model, including cliff-edge effects
  - Careful use of scenarios can be used to ensure cliff-edge effects are considered

Hazard Assessment – Dam Failure

- Most dams of interest are regulated by the U.S. Army Corps of Engineers, FERC, or the Bureau of Reclamation
- Up to now, utilities have requested deterministic information from the regulator via the NRC
- Performing a risk assessment for dams not under the control of the utility is challenging
  - The relevant information is not available
  - The government agencies that regulate dams have an agreement that only they will assess the risk of their dams
- A PRA is not treated as security-related information and any risk information from a dam regulator needs to be provided in a form that isn't tightly controlled
- Potential Solution: partnership with NRC and dam regulators to decide what data can be shared, how to generate it, and how to share it

Human Reliability Analysis (HRA) for XFPRA

- We have an existing framework for HRA for external events, and, in general, this can be applied to external flooding
- External flooding has specific challenges that still need to be addressed (e.g., for actions that take place prior to the arrival of the floodwaters during the warning time)
  - How is the decision made to initiate actions to prepare for the flood (e.g., are the cues subject to interpretation)?
  - What are the failure modes involved in performing the actions (e.g., what are the failure modes of building a sandbag wall)?
  - Under what conditions would Operations not allow personnel to work outside due to personal safety concerns?
- Need to collect operating experience to inform our methods and identify gaps
- Need to understand how the HRA picture might change with correlated hazards (e.g., concurrent high winds and flooding)

Together…Shaping the Future of Electricity

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3.3.10.2.4 Idaho National Laboratory, Zhegang Ma, Ph.D.

External Flood Risk Analysis -- From Probabilistic to Computational Risk Assessment

Zhegang Ma, Ph.D., P.E.

www.inl.gov

Idaho National Laboratory

3rd Annual NRC PFHA Research Workshop
Washington DC, December 4-5, 2017

Idaho National Laboratory

External Flood Risk Analysis – the Need

- External flooding risks are real and could be significant
  - Interrupt offsite power
  - Threaten plant structures and mitigating components
  - Limit plant access
  - Potential for either safety or economic impacts

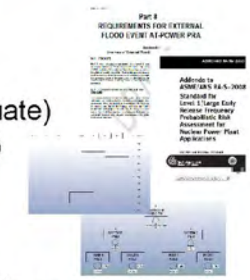
- External flood risk analysis could be used to
  - Identify plant flood vulnerabilities
  - Provide inputs to risk-informed decision making
  - Evaluate event/condition significance

  AND
  - Protect Public Health and Safety

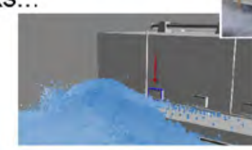
2

External Flood Risk Analysis – What We Have and What are Challenges

- What Do We Have?
  - Revised ASME/ANS external flooding PRA standard
  - Existing PRA methodologies (classical ET/FT but adequate)
  - Existing PRA models (internal event, internal flooding...)

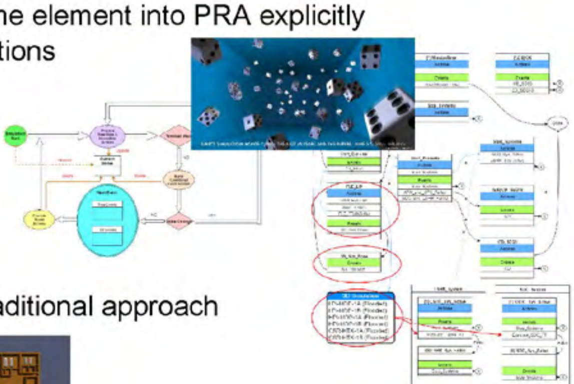


- What are Challenges?
  - Hazard analysis: IE frequency, concurrent hazards...
  - Fragility analysis: component failure probabilities with different flood height
  - Plant response modeling:
    - Spatial: location, location, location...
    - Temporal: sequence/human action are time-dependent...
    - Mechanics: flooding effect, multi-physics phenomena...
    - Topology: multi-state vs yes/no, causal links...

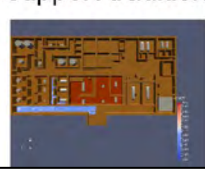


External Flood Risk Analysis – From Probabilistic to Computational

- Advancing Probabilistic RA to Computational RA
  - Improve state-of-art PRA model from classic ET/FT model to integrated simulation-based dynamic PRA (or CRA)
  - Enhanced computation capabilities
  - Static -> Dynamic: by adding time element into PRA explicitly
  - Integrated PRA: through simulations
    - Monte Carlo simulation
    - 3-D physical simulations
    - Mechanical simulations



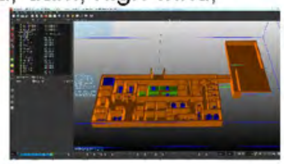
- Potential Roles
  - Stand along analysis tool
  - Supplemental role to support traditional approach



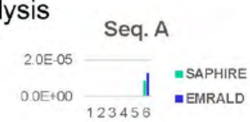
External Flood Risk Analysis – the Path Forward

- Challenges
  - Methodologies (site simulation, 3-D flood simulation, “smart” Monte Carlo simulation for extremely low probability...)
  - Resource (3-D plant modeling and beyond)
  - Uncertainties

- The Road
  - NRC project: local intense precipitation case study
  - DOE/RISMC projects: case studies on external flood, dam, high wind, seismic hazards



  - Selected scenarios -> full PRA model
  - Other external flood mechanisms
  - Concurrent external hazards
  - Able to address multi-unit risks in one integrated analysis



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3.3.10.2.5 Westinghouse, Ray Schneider

Perspectives on External Flooding Probabilistic Risk Assessment: Gaps and Challenges
Risk Analyst Perspective

Ray Schneider

Fellow

Westinghouse Electric Company

NRC 3rd Annual Flood Workshop (2017)

Westinghouse

1

Considerations for Constructing an External Flood PRA

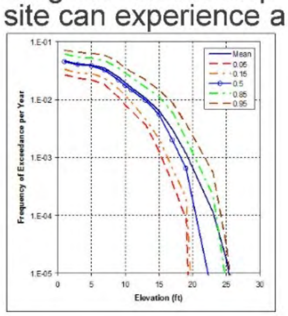
- Characterizing the Initiating Event
- Fragility of Flood Protection SSCs/Barriers
- Treatment of Preventive actions and organizational behaviors
- Characterizing the Plant Initial State

Westinghouse

2

Characterizing the Initiating Event

- A single flood hazard curve may mask PRA important parameters
- Flood Hazard Curve is typically considered a singular relationship relating the frequency of exceedance per year that a site can experience a flood > height/elevation, H.
- Hazard Curve is reasonable simplification for design applications but reflect only one dimension of the cumulative impact of multiple similar but independent hazards if they occur



- Lacks information needed to develop an external flood PRA and to evaluate associated hazard risks

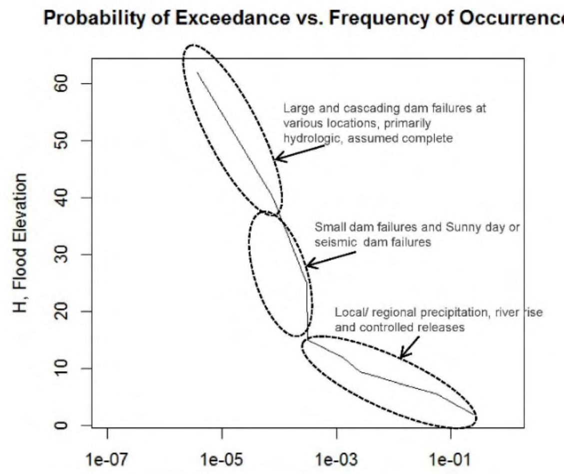
Westinghouse

3

Combined Dam Failure / Precipitation Hazard Curve Developed from Multiple Related Mechanisms

Single curve masks impact of :

- Presence of Pre-Existing Flood Challenges
- Warning Time
- Coexistent Hazards



Dam Failure/Precipitation Hazard Curve

Westinghouse

Need for Disaggregated curves can capture the key characteristics of the hazard event

4

Impact of Co-existent/correlated Hazards:

- Flood elevation may be impacted by wind induced wave "run-up";
  - Wind effects may impact human performance.
  - Elevation / run-up effect typically not significant unless associated with hurricane type winds or hazard has cliff edge in vicinity of still water levels.
- Seismic dam failures can have accompanying seismic impact at site:
  - Limit access paths.
  - May impact communication.
  - Reduce equipment availability.
  - Local/on site impact can create distractions.
  - Potential floodwater ingression into structures through damaged penetrations, structural deformations, etc.

Westinghouse

5

Fragility of Flood Protection SSCs

Fragility understanding generally limited to operating equipment and traditional structures

Flood Risk may be dependent on failure/degradation/leakage of atypically analyzed items (e.g.):

- Penetration seals
- Temporary walls/barriers (inflatable barriers, sand bag walls,etc.) (Quality of barrier installation)
- Small portable, commercial equipment (e.g., sump pumps)
- Seismically induced structural degradation (cracks) (?)

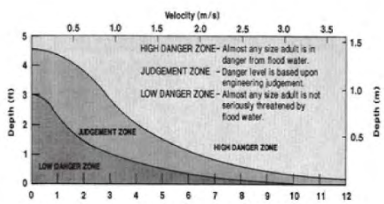
Westinghouse

Treatment of Preventive actions and organizational behaviors

Traditional treatment of trained human actions focus on procedural responses with defined cues in an anticipated environment

Plant flood responses can include:

- Organizationally driven flood actions with uncertain trigger points and uncertain resource loads, uncertain flood levels, etc.
- Potential for flood induced "cliff edge" dominated actions
- Consideration of actions within complex environments and unique personnel hazards
- Overall actions that look more like complex PERT diagrams resulting with multiple varying probability end states



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Considerations in Characterizing the Plant Initial State

Typical plant PRAs occur with a single plant state and defined plant condition. Success is establishing a defined safe shutdown condition.

Initial plant state is known prior to external flood but, flood may dictate alternate shutdown/operational states

- Success of actions to shutdown and re-configure plant for hazard not guaranteed. Leads to multiple shutdown states with differing degrees of flood protection and possible recovery actions
- Duration considerations may complicate definition of mission time.
  - Time to shutdown and re-configure?
  - Time for flood to recede from site
  - Something else?
- Multi-Unit considerations generally apply

Adds complexity and may require additional guidance

Westinghouse

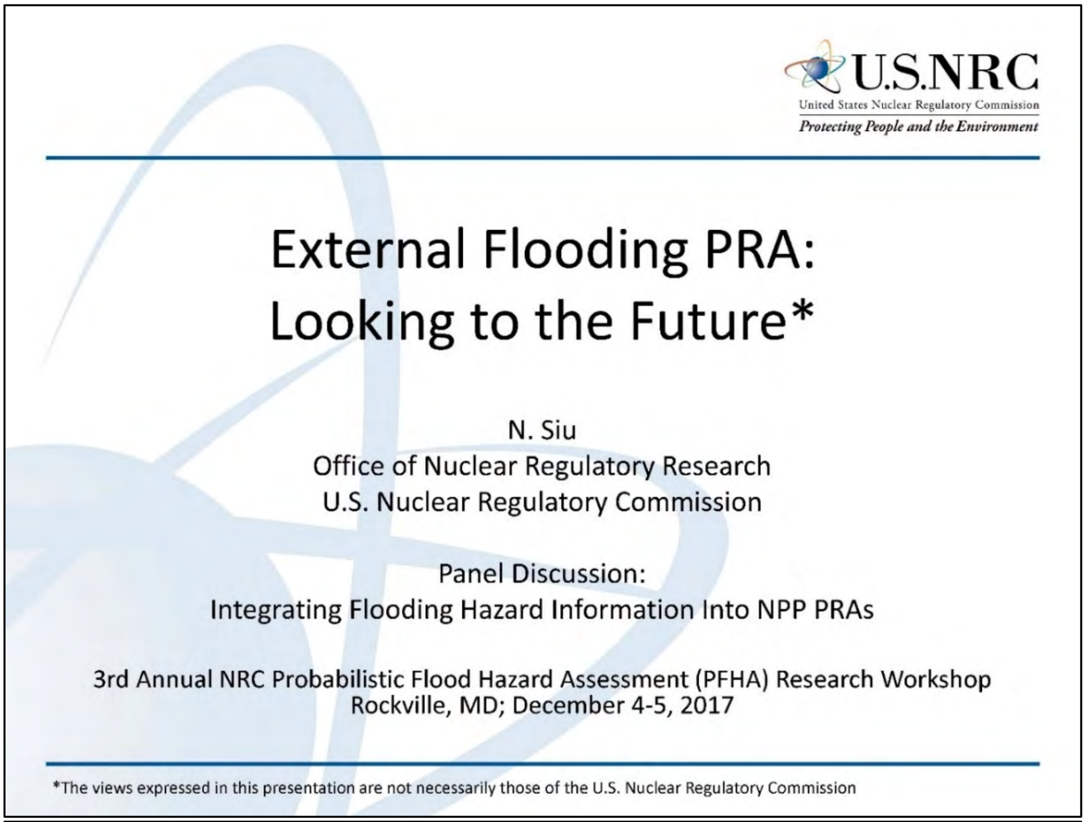
8

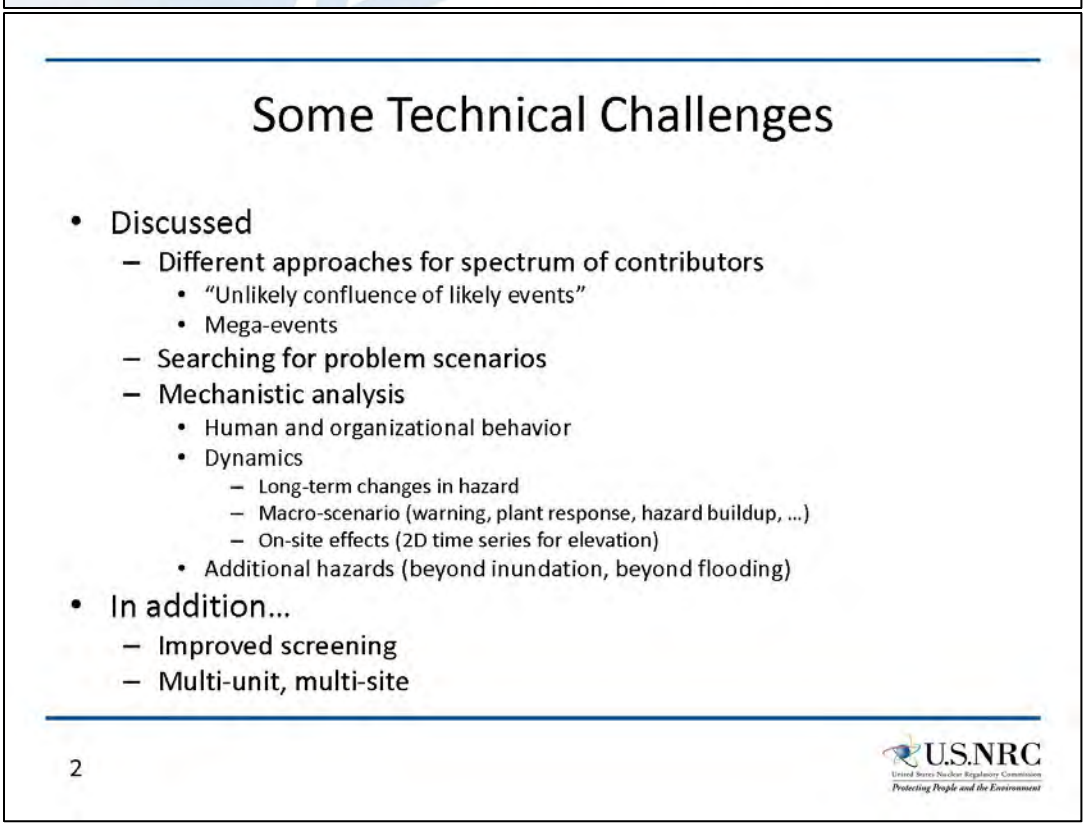
Questions?

Westinghouse

9

3.3.10.2.6 U.S. NRC, Office of Nuclear Regulatory Research, Nathan Siu, Ph.D.





An Improving Situation

- Recognition of potential importance
  - "Other" external hazards => full attention
  - PRA standard update
- Broad interest
  - Multiple agencies, international working groups (e.g., OECD/NEA/CSNI Working Group on External Events)
  - Potentially useful methods, models, tools, data, solutions
- Computational technology
  - Scientific simulations including uncertainty: natural language for multidisciplinary analysis, addressing dependencies
  - Knowledge engineering

3

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Cautions/Reminders

- R&D prioritization considerations
  - Need to be purposeful (limited resources) vs. the "Easy Button"
  - Precision of entire risk assessment
  - Balanced use of video
- Limitations of "repurposed" analyses
- PRA uncertainty analysis amplifies typical simulation challenges
  - Input data validity (distributions, correlations)
  - Simulation validity for combinations of parameters
  - Extracting meaning from massive output
  - Treatment of model uncertainty
- "Risk" includes qualitative as well as quantitative information

4

U.S.NRC
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Protecting People and the Environment

3.3.10.2.7 Discussion

Question (Tom Nicholson, U.S. NRC):

I'm fascinated to hear from NEI that you are welcoming the concept of a pilot study: you want more than one. So, the question really comes down to: what would be the attributes of the pilot studies chosen? What are you looking specifically for? What would be the objective? For instance, would you want to do a PRA in which you looked at combined events, that Ray brought up and others have brought up? The argument is that it's a systematic disciplined way of looking at events combined events and what is risk significant and what isn't was significant? So, if you can answer that, Victoria and Frances, and other people might want to chime in as well.

Response:

Sure. I think what we want to be doing is doing a pilot with a plant that could represent the full spectrum of events and I think also part of the methodology that we would pilot would need to be some sort of screening process and I think that has to be part of any kind of PRA methodology process and so we'd have to pilot that screening process and make sure that that was robust and practical as well.

Response (John Weglian, EPRI)

I think from my perspective even though we're here at the NRC, we would probably want international participation in pilots to make sure that it's not US-centric. Any guidance that WPRI produces: we are going to be focused internationally as well as domestically.

Question (Joseph Kanney, U.S. NRC):

Since you mentioned the phased mission concept: what I was wondering is how does - when you mentioned that I immediately thought back to Victoria's comment about sort of doing things piecemeal and I was wondering - how do we do phased mission approaches without stepping into the trap of having conservatisms built into each of the different phases that we didn't really notice until we put everything back together?

Response (Nathan Siu, U.S. NRC):

I think those are kind of different issues but the issue with piecemeal had to do with specific phenomena. So, for example heat release rate for a fire or let's say the treatment of detection of fires. There are different pieces that are all the things that need to go into a PRA. And, yes, if you are conservative in each of these pieces you will get a conservative answer unless you've missed something that you haven't included in your model at all. Phased mission simply says I'm going to discretize the scenario into pieces (and of course not to pay attention to the handoffs) so I lead from this part of the scenario to this part of the scenario. There's nothing that forces me to be conservative about that. I may, as a business decision, choose to do that if I don't want to take the time to analyze things to the level of detail that maybe could be done and maybe I want to take a conservative shortcut. But these are things that are done in regular PRAs. It’s I think the question of degree and extent, but I really think those are two separate issues. And, Victoria, of course…

Response (Victoria Anderson, NEI):

I think he may be a little closer than that. I mean, when we talked about in fire PRA and the piecemeal approach and the different phenomena: the issue was that they all stacked up on each other as different steps and I think if you take the phased approach you could run into the same kind of danger.

Response: (Nathan Siu, U.S. NRC):

Obviously, your intent would be a realistic analysis and given the resource constraints that you've got. But, yes, if you have conservatism at one level of the one phase, it could propagate. In fact, this is one of the problems with the dynamic analyses is when you start getting into the details. If you start making simplifications in part of the analysis you can end up with things that just make no sense whatsoever by the time you get to the end of the analysis. You have operators responding to cues that they aren't going to see in practice because of the simplifications made earlier. So, there's a certain degree of detail that has to be taken care of if you're going to do that kind of analysis.

Question (Moderator Fernando Ferrante, EPRI):

Let me ask the question to Chris. You had an interesting bullet where you said, from the civil engineering community, what does the nuclear engineering community expect to get? And so, we had discussions during this workshop on essentially paleo-flood, how to do coastal surge, what are the different numerical models – L-moments, Bayesian Inference… let me ask, maybe Ray or John or anybody else the question that Chris posed. I mean, we are looking at a different world and different communities here. I think we all do risk assessment, at the end of the day. I haven't seen anything new under the sun in risk since we said hazard: risk triplets hazards, impacts, consequences and so forth. And so, from somebody who is doing plant analysis and we have several that have done this before, what have you guys heard and what you are looking to see forward to be able to have something useful. You know I always was the person, at some point, until I got more educated, to say just give me that number and tell me what the flood frequency is until I realized it's not that easy. But what do you guys see moving forward? Ray John, do you want to take a stab at that?

Response (John Weglian, EPRI)

Can you rephrase that in a simple question?

Follow-up:

If you had all the money in the world and all the time in the world and you were going to do a pilot and you have a plan and he said, to the community, to the hydrologic community, tell me something I can use? Given your experience in having seen some of this, what would you hope to see; more than that, are you going to use?

Response (John Weglian, EPRI)

I see multiple parts that need to feed in to get to the end goal and the end goal is to assess the risk. The end goal is not to get a CDF number – right. It's to evaluate a plant and understand the risks to the plant so pieces of that are the hazard and different hazards have different uncertainties. They have different modeling techniques. Simulation may be extremely useful for some and may be less useful for others. So that's the piece: you've got how do you do the assessment of the plant responses? And so, I mentioned the plant walk down. But that's one way to assess that. Right now, for barrier fragilities for example, typically we assume kind of a go/no-go - the water level gets to this high on the door and we assume the door fails. There's a there's a more nuanced approach to that that may or may not change your risk insights. So, you don't want to just put in a fragility which greatly complicates your analysis just to have it in there when the risk insights would be the same otherwise. Then once you've got your model for all your different hazards - I envision if you're at a site and you have three applicable hazards that didn't screen, you would effectively have three separate external flooding models that you could run independently of each other because they may have completely different site impacts. That's how I see it being put together. You might get risk insights from one floating mechanism and not another. So, at the end of the day you have to look at your total package and what do you learn from it? One thing I want to address: so, I mentioned before - do the risk insights change and one of the concerns that that I have with the SHAC-F process is – is it going to give you a different answer? If it cost five million dollars to do a site-specific SHAC-F and it costs a hundred thousand dollars to do the equivalent of a level one that you just do in-house with you someone else doing a peer review for you and you don't get a different risk insight at the end of the day. If it doesn't change any of your decisions that you would make - you wasted the money if you did the five million dollars thing. So, we need to understand what's the benefit of doing all these extra things? And that might also be site-specific. It might be that at this site it's not going to change the answer enough to make further refinement of the analysis worthwhile and at another site it might be completely worthwhile because cliff-edge effects, or whatever. That it's extremely important that we understand the cascade of events that happen there.

Response (Ray Schneider, Westinghouse):

I'd like to take it from you. I think the question you were kind of asking is: what are we getting from the hydrologic community in terms of what we what we need? I think that the thing is that when you develop the hazard curves in a number of instances you're actually developing a series of curves that you basically are putting this on one another which have different characteristics. And so, for the events I have, again, different levels of run-up because you have different wind velocities or wind speeds. You may have different accumulation rates or information like that that may be relevant in, basically, dealing with downstream work and PRA, like human factors or something. So, if there's assumptions you're making that that would likely affect how that event is actually proceeding, not so much just this total elevation. And, say, well, I have a 10^{-5} 110 foot flood, or something like that, but there's information that goes along with that that created that that may be made up of five or six different types of floods and have different characteristics. That would be of used in developing the initiating event that basically drives the rest of the model because without that it's really hard to really understand the pieces that are going to follow. And this mainly comes, in my instance, from dam breaks, dam events: you can have early releases, you could have random failures of the dam , you could have catastrophic failures: I mean with the full-on, totally catastrophic overtopping kind of failures and as a result of that they all go into the same curve: but every one of those is a different event. And so, we just have to be careful that if you want us to view it as one event, where one kind of event with all of the same characteristics, then that's fine. But if there really are multiple different events in it: somehow you have to figure out a way of communicating that information to the people downstream.

Response (Nathan Siu, U.S. NRC):

I know John has a question but I'm going to jump in. The part about insights - of course who would argue about the importance of insights. But I also want to say that insights aren't necessary the only metric and the only reason why one does something. You obviously have to have confidence in the results of the study. You have to believe the insights have sufficient basis and if this expensive process gives you that increased confidence, and that's an if, then you could say that might be worth doing even if in the end you don't get the a very different answer. And of course, the classic example people have these jokes about HRA and the various calculator used for HRA which are totally random. But would you indeed base a safety decision on that - even if you had some belief that you were going to end up with a number that kind of was similar to what the HRA might produce - I don't think so. The other thing of course is that insights are very dependent on the purpose of the analysis. So, a level one study you get certain kind of insights, a level two study may give different insights. I think a lot of times in PRA we do these game-over modeling assumptions and say, look, I know this is going to failure so I'm not going to model it anymore and that's fine for the purpose of analysis. But you're not going to gain any insights, perhaps, about what people might do after you reach that particular point. So, helping operators, perhaps, respond to the event in this extreme situation- you’re not going to get that insight. So, it might be worthwhile pursuing with a more detailed model. But again, it depends on the purpose of the study.

Comments (John England, USACE):

I don't have a question. I just have a whole page full of comments, so I'll keep it brief. For those who haven't - who missed my presentation 2013, we started flood hazard analysis at Reclamation when I walked in there in 1997 and we've gone through an inventory of 350 dams and made major decisions on those facilities. So that one key difference I came up with earlier was Reclamation, which I can't speak for, but I can speak for the Corps of Engineers: we're self-regulating. So, we use risk to prioritize limited funds across portfolios. So, you can rack and stack when you only have 40 plants, all potential failure modes (PFMs), for those individual plants which may add up to our matrix of the number of facilities we have. But we've made structural decision modifications on those facilities based on these hazard curves, so I encourage you to look at some of those reports and what’s behind them because besides water levels we have durations, which are the key triggers for things like Orville, which Ken Fearon presented. I think one of the barriers: two of them. One is the industry's lack of moving toward PRA in the first place for floods - which I think Reclamation led 20 years ago - is now upon us. You've seen all the things talking about that. But the pieces you’ve been missing with this panel and that we've experienced over the years is the integration of the hazard folks with response folks - so you can target specific hazard curves for those things like duration for the spillage of the cracks in that joint in Orville which drives - that is totally duration driven issue - and you can quantify that. It's very easily done. And as far as uncertainty is concerned we've provided - I think Joe Wright mentioned this earlier - what uncertainties do you or what level of confidence do you want? So, for various water levels we have full uncertainty but they're full uncertainty. So, if you want to choose conditional non-exceedance probability at 97 a half % or 84% we have that information in there. So, I think there's a disconnect in terms of at least what I'm hearing here is the usage of that information in the PRA process and structuring of individual decisions on event trees.

Comments (Moderator Fernando Ferrante, EPRI):

John can I comment on that before you continue. So, I think one of the things that it's interesting that you bring up is and this is the kind of the different communities coming together. I mean I can't speak for the NRC, of course, anymore, but risk is tremendously used within the NRC or risk management. So, I understand your point. I mean it is used right now in terms of if a piece of equipment is out of service, how you rank whatever actions you might need to take with that. It's used for risk ranking on all the important components. It is used for risk ranking on fire protection. So, I think there is a framework in the nuclear world. When it comes to flooding is where we're kind of… I can speak because I took the training at the Bureau when you were there, and I was very impressed with a framework insight. I can see putting aside the two frameworks and then saying okay how do we come together when flooding is the topic? And what is it that can be cross-pollinated given the requirements that you need to have for a nuclear grade PRA with flooding hazard within that. So, I fully hear you. I think nuclear risk has gone very far. I think the consequence is there. I think there's a gap presented here. I mean we do go to consequence analysis, radiological consequence analysis. Our models are – they tend to become surrogates because they stop a core damage. NRC is doing a level three which is when you take it all the way from the beginning to the end. I think your point is fully well taken. I think the question is for flooding is where some gaps are. And then how do we bring this community. For example, if somebody were to do a very detailed NPRA and they get all the sequences, now how do we give it to Ray or somebody within the utility who have millions of cutsets coming up of other things and now they have to prioritize that information and put it… so I ask the question because I had a question in hidden in my mind which was the narrowing of the information so somebody within the nuclear plant response (let me put it that way so we don't divide people in PRA bends) uses that in some manner. I don't know if that aligns with your comment in a way.

Comments (John England, USACE):

I'm looking at my former coworker here. If the integration, so when the report is producing you get that report. It's like back to Chris's point about visualization – we completely agree on that. I don't have anything profound standard for visualization which we need more of. Because we have found over the years that we produce a report. Then engineers in response get it two years or five years later and they don't have questions about it. So, then it's an integration and part of the PRA process, as you probably already have facilitated, to integrate that information collectively and then ask for additional key information when you need it because there's gaps all along the way. The other thing I could comment on - back to case histories - I'll put Joe Wright on the spot here because, at least when I was at Reclamation, we modified facilities. Meaning we use taxpayer money to improve them and reduce risk (structural). Some cases in the Corps now we're doing non-structural solutions. So, having a library of which facilities you've gone through on fire hazard protection or maybe some seismic retrofit and gone through, so you can holistically start to use that as a screening process to gain information might be useful.

Question (Joe Wright, Reclamation):

My question is a little unrelated, a little different. My question kind of goes back to John Weglian. I heard you mentioned a couple of times dealing with non-stationarity and this was something that we wrestled with quite a bit in Reclamation. I just thought since everyone's here I might open this up for some discussion on how we might deal with non-stationarity. One method that we have at Reclamation and are comfortable using is the fact that we review our facilities every eight years, we see the non-stationarity problem kind of taking care of itself within that process. But that doesn't address any kind of final design or corrective action type fixes where we're going to make a decision based on the non-stationarity of a project. I'm just worried that sometimes when I hear of these decisions. Are we taking a step backwards from risk-based decision making and going back to the old deterministic PMF type problem? Any thoughts?

Response (Victoria Anderson, NEI):

I'm actually going to break in before John. We don't we don't do risk-based regulation at all. It's all risk-informed meaning that we're never abandoning the first deterministic principles in the first place so that's something that shouldn't be an issue

Response (John Weglian, **EPRI);**

In terms of how you update there's kind of two pieces of that. So, PRA models typically get updated every two fuel cycles. So, every three to four years you do a re-evaluation of your data and I would imagine with external flooding you would be looking at that. I know EPRI has activity underway that looks at new information for external hazards and see does that fundamentally challenge the existing base of information. Hurricane Harvey was an example. They looked at that event and said does this challenge our PMP analyses and things like that right. So, there's this process in place that looks to see is there new information that we need to consider right now, is it information that we add to the database that you include over time. As an industry we are looking for those kinds of things. I would say the potential problem with relying on the recent change in data: you're getting what is the non-stationarity of the one in ten-year type events. Maybe you have no idea how that's affecting the one in a million which you really had no idea anyway because your uncertainties were so large. I think when you're looking at that range the only way to really handle it, with these uncertainties, is with sensitivity studies. You do a sensitivity study and say: what if I was wrong by a lot? I don't know what a lot is: is a lot 20%, is a lot 50%? I don't know. But you do an assessment there and you know if I was off by a lot does the answer fundamentally change or not and if it's effectively the same risk insights. Then you feel confident that your model is giving you good risk insights. If it is fundamentally different now you might want to look at why is it different. Where does that come from? Is it a particular cliff edge effect and if it is maybe I want to focus on that and try to understand what I can do to reduce that impact on my client.

Question:

If you have limited resources, what problem will you tackle first? Which problems are really bugging you as other industry, NRC or NEI or EPRI?

Response (John Weglian, EPRI):

Everybody's got limited resources right, so everybody has that problem. I think it's probably site-specific. I think we have in most cases a decent path forward on the hazard risk assessment. We saw a lot of work today on that, so I think we have a good path forward there. I would focus the efforts on how to build the PRA model with what we have and identify is there something out there that's missing that that we need to invest in more research to address that issue.

Response (Christopher Cook, U.S. NRC)

I guess from my standpoint at the NRC about 10 years and I was working for about five years before as a contractor. I think if I look at that 15-year period and I look at where we are today both of my gaps are more: how do we bring these roles together? That's what John was getting at with Joe; in some ways, as Victoria mentioned, getting on with pilots. It's taking what we have: it's what this workshop is about, what everyone has been doing for the past several years on this and now looking to the future. We're looking at how we direct it going forward taking what we have and then actually using it to keep it going then those studies.

3.3.11 Day 2: Session 2D - Future Work in PFHA

Session Chair: Mark Fuhrmann, NRC/RES/DRA/FXHAB

3.3.11.1 Future Work in PFHA at EPRI John Weglian*, EPRI (Session 2D-1; ADAMS Accession No. ML17355A078)

3.3.11.1.1 Presentation

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Future Work in PFHA at EPRI

John E. Weglian
Senior Technical Leader

3rd NRC External Flooding Research Workshop
December 4-5, 2017

Near-Term EPRI External Flooding Research

- Collection of paleoflood evidence
  - Report at end of 2017
- Use of paleoflood data in risk-informed approaches
  - Research in 2017-2018
- Estimation of frequency of hurricane-driven storm surge
  - Research in 2017
- Guidance on conducting PRA external flooding walkdowns
  - Research in 2017

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External Flooding PRA Walkdown Guidance

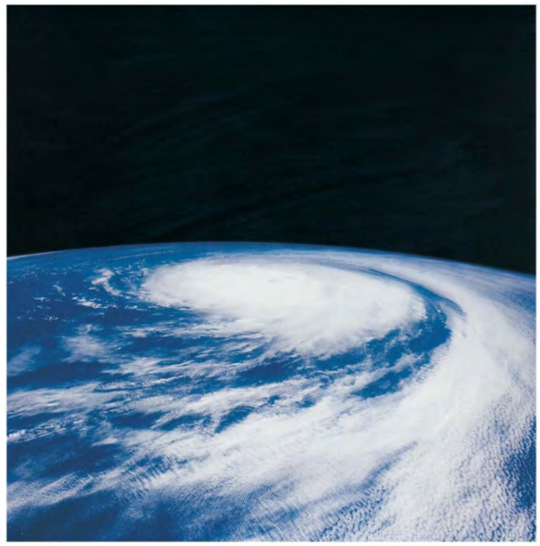
- External flooding walkdowns for deterministic flood analyses (such as for answering the 50.54(f) letter) may not be sufficient for an external flooding PRA
- EPRI will develop a guidance document for conducting a walkdown to support an external flooding PRA
- This guidance will help utilities use the results of a PFHA to assess the impact on the site from the external flooding hazards

Paleoflood Data

- Paleoflood data has the potential to inform the flood-frequency curve in the 10^{-2}/yr to 10^{-4}/yr range
- Process involves:
  - Finding paleoflood evidence
  - Interpreting the evidence to estimate flood stage or discharge and date for each flood
  - Confirming that the conditions at the time of the floods were applicable to the current conditions
  - Estimate the flood parameters of interest at the site
  - Adjusting the flood-frequency curve based on the applicable data
- EPRI is publishing a report on the paleoflood evidence in 2017 – EPRI ID: 3002010667
- EPRI is prioritizing research on the other aspects of using paleoflood data

Hurricane-Driven Storm Surge

- EPRI is conducting research on the use of simulations of hurricane parameters to estimate the storm surge at a given site
- Research on this topic is expected to be complete in 2018



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External Flooding PRA Walkdown Guidance

- EPRI is developing draft guidance for performing external flooding PRA walkdowns
- EPRI plans to pilot the guidance at one or more sites in 2018
- EPRI would then incorporate the lessons learned from the pilot site(s) before issuing the final guidance as a Technical Report

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Potential Long-Term External Flooding Research

- Seiche and tsunami frequency estimation
  - Leverage existing international research
- Dam failure
  - Possible coordination with NRC working with dam regulators
- Correlated hazards (e.g., storm surge and wind)
  - Research would investigate whether a simple correlation (e.g., match the 10^{-4}/yr winds with the 10^{-4}/yr storm surge) is sufficient
- Flood barrier fragility
  - Current flooding PRAs treat flood barrier success deterministically (e.g., a door fails at a particular height)
  - Additional methods and data may provide a better estimation for barrier fragilities

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3.3.11.1.2 Questions and Answers

Question:

I think a side benefit of doing a fragility analysis will be bringing this into the PRA model and as a parameter that can then be addressed with importance measures.

Response:

There're additional benefits to including that: you can make it an element in your online risk assessment and when you do maintenance and you've got the door propped open you can actually fail that directly and see exactly what that impact is. If you do that for every door in the plant, you've greatly complicated the model, and you may have made it unquantifiable in a reasonable amount of time. So, you need to you need to look at the balance: where does it make sense to do that… where does it not make sense. And I would imagine that you probably wind up with a mixture. Here are my most important doors and I'm going to treat those with the fragility and the others I'm going to treat deterministically.

Question:

You mentioned tsunamis. This workshop didn't focus on tsunamis but I'm sure you're aware the NRC's produced some recent NUREG reports on tsunamis especially for the East Coast of the United States. Are you guys reviewing those?

Response:

I'll have to look at that. I've been a little busy.

Question:

On your storm surge research, is the work that you're doing now for a single site or is it regional?

Response:

It's based on work that was done for a particular site, but the guidance should be general.

3.3.11.2 Future Work in PFHA at NRC Joseph Kanney, Ph.D., Meredith Carr*, Ph.D., P.E., Thomas Aird, Elena Yegorova, Ph.D., and Mark Fuhrmann, Ph.D., Fire and External Hazards Analysis Branch, Division of Risk Analysis; and Jacob Philip, P.E, Division of Engineering, Structural, Geotechnical and Seismic Engineering Branch, Office of Regulatory Research, U.S. NRC (Session 2D-2; ADAMS Accession No. [ML17355A079](ML17355A079))

3.3.11.2.1 Presentation

Expected NUREG/CR Completions in FY18

- Guidance on Application of State-of-Practice Flood Frequency Analysis Methods and Tools (USGS)
- Technical Basis for Extending Frequency Analysis Beyond Current Consensus Limits (USBR)
- Research to Develop Guidance on Extreme Precipitation Frequency in Orographic Regions (USBR)
- Technical Basis for Probabilistic Flood Hazard Assessment – Riverine Flooding (PNNL)
- Quantifying Uncertainties in Probabilistic Storm Surge Models (USACE)
- Effects of Environmental Factors on Manual Actions for Flood Protection and Mitigation at NPPs (PNNL)
- Modeling Plant Response to Flooding Events (INL)
- Regional Climate Change Projections: Potential Impacts to Nuclear Facilities (PNNL)

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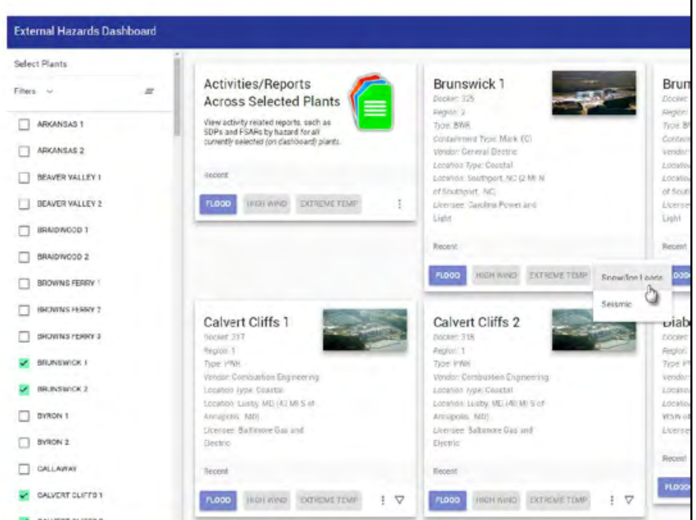
External Hazard Information Digest (INL)

- Flood hazard population expected complete FY18-Q2
- Expansion to support Process for Ongoing Assessment of Natural Hazard Information (SECY-16-0144; SRM-SECY-16-0144):
  - Tool for collecting, aggregating, reviewing, and assessing information on an ongoing basis
  - Other Hazards
    - Expanded flooding content
    - High Winds
    - Extreme Temp/humidity
    - Seismic



FY18 – New External Projects and Internal Initiatives

4

Critical Review of Dam Risk Assessment State of Practice

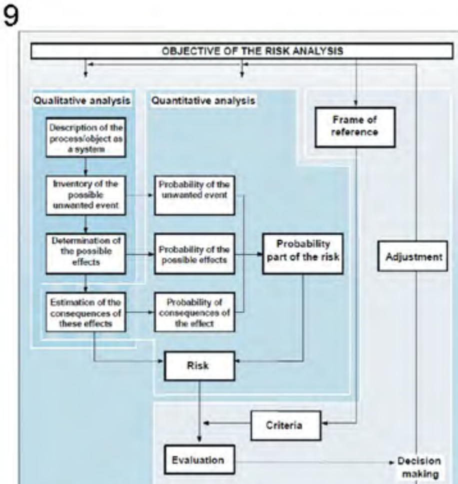
- *David Watson, Scott DeNeale, Brennan Smith & Shih-Chieh Kao (ORNL)*
- *Gregory Baecher (University of Maryland)*
  - *NRC PM: Carr*
  - Project Timeline: Sept 2017 to Apr 2019

Objective

Develop technical basis for guidance on application of state-of-the-practice approaches, methods and tools for dam risk analysis to inform assessment of flood hazards due to dam failure.

Scope

Assess methods for characterizing and quantifying key uncertainties, as well as propagating these uncertainties through the risk analysis procedure to support risk-informed decision-making



Parts of risk analysis
(Adapted from Vrijling and Van Gelder 2002)

Critical Review of Dam Risk Assessment State of Practice

Key Tasks

- Conduct workshop with federal agencies, academic researchers and private industry to review current state of practice in dam risk analysis
- Summarize current state of practice with focus on development of fragility information for
  - key components
  - control systems
  - operational procedures
- Review key process uncertainties, their characterization, and the degree to which they are propagated in state of practice approaches

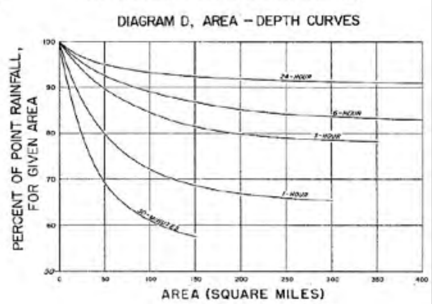
Folsom Dam Gate Failure (1995)

Application of Point Precipitation Frequency Estimates to Watersheds

- *Shih-Chieh Kao, Scott DeNeale (ORNL)*
  - *NRC PM: Yegorova*

- Project Timeline: Oct 2017 to May 2019
- Current precipitation frequency products (e.g., NOAA Atlas 14) are mostly developed for point rainfall
- Areal reduction factors (ARFs) are needed to convert these point precipitation estimates to watershed estimates for H&H modeling
- ARFs in common use suffer from several key deficiencies:
  - Limited/outdated data
  - Small area sizes (up to 400-mi^2)
  - Do not vary with location, return period, or season

Example ARF curves (from TP-29)

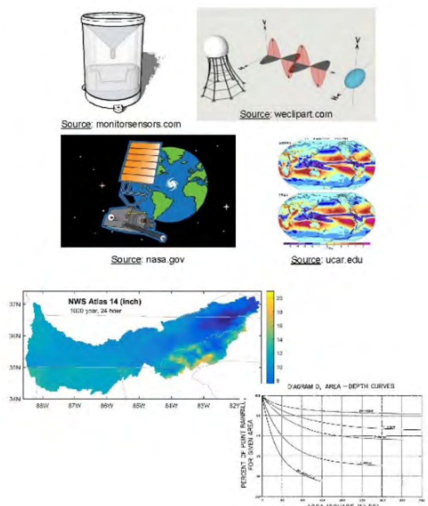


Source: Technical Paper No. 29; noaa.gov

Application of Point Precipitation Frequency Estimates to Watersheds

Project Objectives

- Provide a summary of available precipitation products that can be used to develop point to area conversions of precipitation frequency estimates.
- Provide a critical review of available point to area conversion methods with a view to addressing the deficiencies in the commonly used empirical methods.
- Demonstrate use of the most promising method/dataset combinations through selected test cases.
- Support the development of future PFHA guidance on ARF



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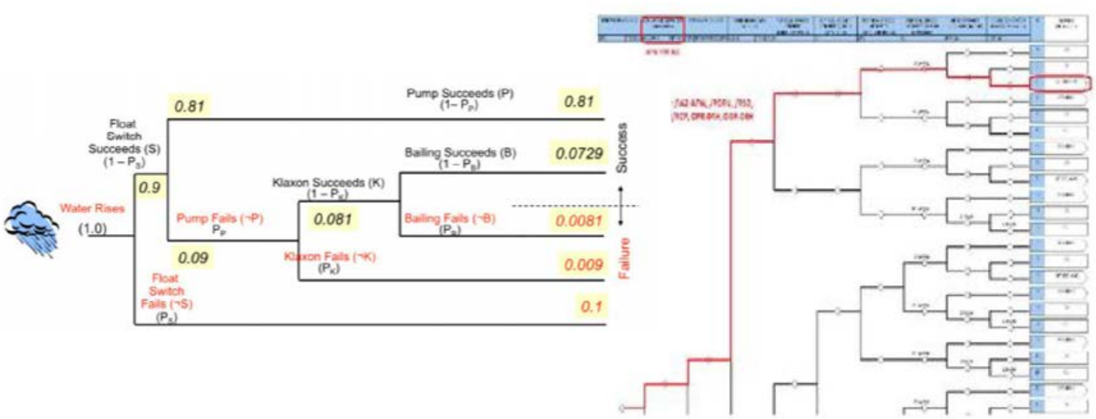
Interfacing Flood Hazard Modeling Outputs with HRA and PRA Models

- Integrate flood hazard into existing models
- Determine important scenarios
- Handle time dependencies (phasing)
- Internal Collaboration



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Projected FY19-20 Work*

*** Subject to availability of funding**

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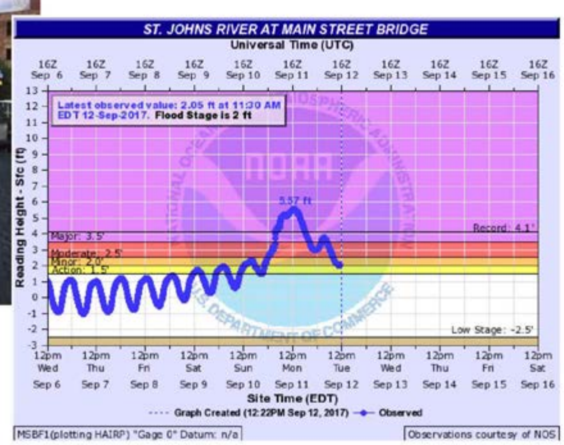
Probabilistic Treatment of Coincident and Correlated Hazards and Their Effects



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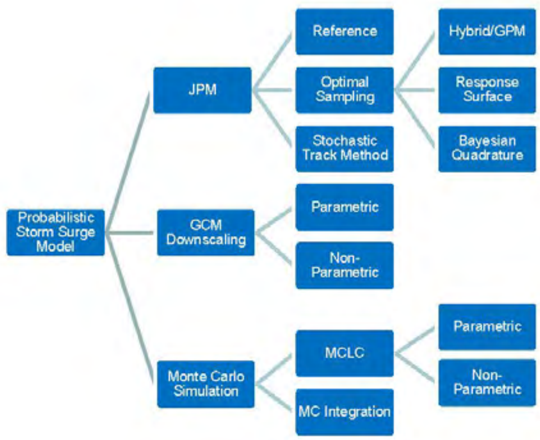
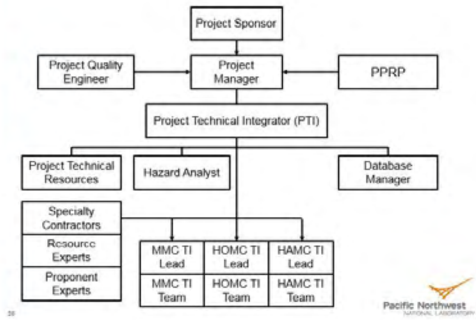
Application of SHAC-F to Coastal Flooding Hazard Assessments





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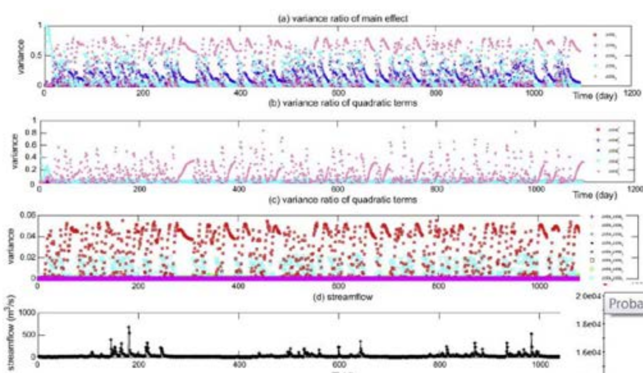
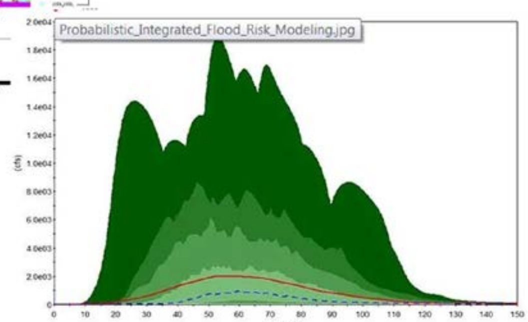
Quantifying Uncertainties in Probabilistic Riverine Flood Models



Contributions to model parameters to uncertainty in model predictions: Fan et al, 2015



Draft Regulatory Guidance


U.S. NUCLEAR REGULATORY COMMISSION
OFFICE OF NUCLEAR REGULATORY RESEARCH

DRAFT REGULATORY GUIDE

DRAFT REGULATORY GUIDE

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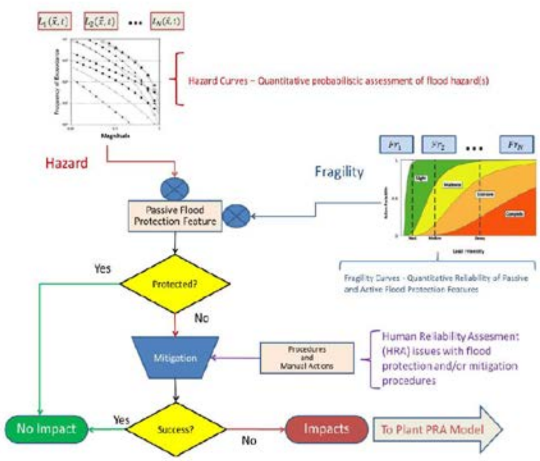
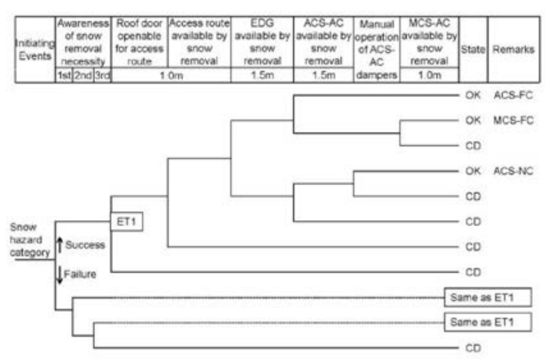
Pilot Studies





3.3.11.2.2 Questions and Answers

Question:

The interface between the hazard and the PRA model… are you working on this in 2017-2018 or I couldn't catch?

Response:

We've started internal discussions within our office to try to get an idea what's going on and we're starting to spread that out to other offices. We'd like to get collaboration because it's such an issue that we want to make sure people from all the different fields get involved before we come out with some sort of hazard guidance that doesn't fill the needs of PRA.

Question:

So, this is budgeted basically?

Response:

Yes. But there's no specific external funding

3.3.12 Day 2: Final Wrap-up Session / Public Comment

Question:

I've mentioned to a couple people this idea: the nuclear industry has a database of component failures and I've noticed the dam industry does not have such a system but a lot of dams, independently, keep track of component issues that they have… is there a way we could leverage the nuclear industry's set-up for the dam industry as well?

Response

(Joe Kanney, NRC): I actually had an inquiry from Marty McCann about this probably at least two years ago. I told him about what the structure is in the nuclear industry, how their organizations, like INPO, collect this information and have databases. I'm not sure where it went after that.

3.4 Summary

This report documents the 3rd Annual NRC Probabilistic Flood Hazard Assessment Research Workshop held at NRC Headquarters in Rockville, MD, on December 4-5, 2017. These proceedings included the following:

- Section 4.2: Workshop Agenda (in the program (ADAMS Accession No. ML17355A081)
- Section 4.3: Proceedings (abstracts at ADAMS Accession No. ML17355A081 and complete workshop presentation package including slides and questions and answers at ADAMS Accession No. ML17355A071)
- Section 4.4: Summary
- Section 4.5: Workshop Participants

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5 SUMMARY AND CONCLUSIONS

5.1 Summary

This report has presented agendas, presentations and discussion summaries for the first four NRC Annual PFHA Research Workshops (2015-2019). These proceedings include presentation abstracts and slides and a summary of the question and answer sessions. The first workshop was limited to NRC technical staff and management, NRC contractors, and staff from other Federal agencies. The three workshops that followed were meetings attended by members of the public; NRC technical staff, management, and contractors; and staff from other Federal agencies. Public attendees over the course of the workshops included industry groups, industry members, consultants, independent laboratories, academic institutions, and the press. Members of the public were invited to speak at the workshops. The fourth workshop included more invited speakers from the public than from the NRC and the NRC's contractors.

The proceedings for the second through fourth workshops include all presentation abstracts and slides and submitted posters and panelists' slides. Workshop organizers took notes and audio recorded the question and answer sessions following each talk, during group panels, and during end of day question and answer session. Responses are not reproduced here verbatim and were generally from the presenter or co authors. Descriptions of the panel discussions identify the speaker when possible. Questions were taken orally from attendees, on question cards, and over the telephone.

5.2 Conclusions

As reflected in these proceedings PFHA is a very active area of research at NRC and its international counterparts, as well as other Federal agencies, industry and academia. Readers of this report will have been exposed to current technical issues, research efforts, and accomplishments in this area within the NRC and the wider research community.

The NRC projects discussed in these proceedings represent the main efforts in the first phase (technical-basis phase) of NRC's PFHA Research Program. This technical-basis phase is nearly complete, and the NRC has initiated a second phase (pilot project phase) that is a syntheses of various technical basis results and lessons learned to demonstrate development of realistic flood hazard curves for several key flooding phenomena scenarios (site-scale, riverine and coastal flooding). The third phase (development of selected guidance documents) is an area of active discussion between RES and NRC User Offices. NRC staff looks forward to further public engagement regarding the second and third phases of the PFHA research program in future PFHA Research Workshops.

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These workshops were planned and executed by an organizing committee in the U.S. Nuclear Regulatory Commission's (NRC's) Office of Nuclear Regulatory Research (RES), Division of Risk Analysis, Fire and External Hazards Analysis Branch, and with the assistance of many NRC staff.

Organizing Committees

1st Workshop, October 14–15, 2015: Joseph Kanney and William Ott.

2nd Workshop, January 23–25, 2017: *Co-Chairs*: Meredith Carr, Joseph Kanney; *Members:* Thomas Aird, Thomas Nicholson, MarkHenry Salley; *Workshop Facilitator:* Kenneth Hamburger

3rd Workshop, December 4–5, 2017: *Chair:* Joseph Kanney, *Members:* Thomas Aird, Meredith Carr, Thomas Nicholson, MarkHenry Salley; *Workshop Facilitator*: Kenneth Hamburger

4th Workshop, April 30–May 2, 2019: *Co-Chairs:* Meredith Carr, Elena Yegorova; *Members:* Joseph Kanney, Thomas Aird, Mark Fuhrmann, MarkHenry Salley; *Workshop Facilitator:* Kenneth Hamburger

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During the workshops, Tammie Rivera assisted with planning and organized the registration area during the conference. David Stroup and Don Algama assisted with room organization. Notes were studiously scribed by Mark Fuhrmann, David Stroup, Nebiyu Tiruneh, Michelle Bensi, Hosung Ahn, Gabriel Taylor, Brad Harvey, Kevin Quinlan, Steve Breithaupt, Mike Lee, Jeff Wood, and organizing committee members. The organizers appreciate the assistance during the conference of audiovisual, security, and other support staff. The organizers thank the panelists, the technical presenters, and poster presenters for their contributions; Thomas Aird and Mark Fuhrmann for performing a colleague review of this document; and the Probabilistic Flood Hazard Assessment Research Group for transcript reviews.

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APPENDIX B: INDEX OF CONTRIBUTORS

This index includes authors, co-authors, panelists, poster authors and self-identified participants from the audience who spoke in question and answer or panel discussions.

APPENDIX C: INDEX OF PARTICIPATING AGENCIES AND ORGANIZATIONS